NAVAL POSTGRADUATE SCHOOL

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THESIS

**EXPLORING THE EFFECTIVENESS OF
THE MARINE EXPEDITIONARY RIFLE SQUAD**

by

Todd M. Sanders
September 2005

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THE MARINE EXPEDITIONARY RIFLE SQUAD**

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Submitted in partial fulfillment of the
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ABSTRACT

This study explores the effectiveness of the Marine Expeditionary Rifle Squad (MERS) in support of Distributed Operations in urban terrain. The Marine Corps is evaluating the Distributed Operations concept as a solution to new threats posed in current operations. In order to employ distributed tactics, a more effective and capable Marine Rifle Squad is needed. The MERS concept seeks to increase the effectiveness of the current rifle squad, enabling smaller, more lethal, and more survivable units. Those issues are explored using agent-based modeling and data analysis. The most significant finding is that the MERS must be evaluated as a system; factors cannot be analyzed in isolation. The two factors that most affect the effectiveness are survivability and lethality. Maximizing these two factors leads to the lowest friendly casualties, highest enemy casualties, and highest probability of mission success. Agent-based modeling provides the maximum flexibility and responsiveness required for timely insights into small unit combat.

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COMMON ACRONYMS

- **AIC**   Akaike's Information Criteria
- **C2**   Command and Control
- **CAS**   Complex Adaptive System
- **DM**   Designated Marksman
- **DO**   Distributed Operations
- **IDF**   Indirect Fire
- **LOS**   Line-of-Sight
- **LSE**   Least Squared Error
- **MANA**   Map-Aware Non-Uniform Automata
- **MERS**   Marine Expeditionary Rifle Squad
- **NOLH**   Nearly Orthogonal Latin Hypercube
- **PC**   Probability of Classification
- **PK**   Probability of Kill
- **RCO**   Rifle Combat Optic
- **SA**   Situational Awareness
- **SSPK**   Single-shot Probability of Kill
- **T/E**   Table of Equipment
- **T/O**   Table of Organization
- **UAV**   Unmanned Aerial Vehicle

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EXECUTIVE SUMMARY

The Global War on Terrorism has introduced the United States to new threats that present new capabilities and that are dedicated to destroying our way of life. Terror organizations have demonstrated the ability to utilize varying and adaptive tactics to inflict mental and physical casualties on the United States and its allies.

In an effort to mitigate the new threats, the United States Armed Forces have begun to evaluate and employ organizational structures, and tactics, techniques, and procedures that vary from traditional concepts. Once again, the infantryman has become the best solution to combat new threats that have applied tactics that reduce the capabilities of modern American combat power. Ensuring the man on the ground is prepared to face the enemy will lead the United States to victory in the Global War on Terrorism. "On today's battlefield, with irregular warfare, victory quite often goes to those individuals who can do something faster, working inside the enemy's decision cycle" (Hagee, May 2005). The Marine Expeditionary Rifle Squad (MERS) will accomplish this. The Marine Expeditionary Rifle Squad is "that distributed close combat fighting capability embodied in the Marines Corps Infantry, to include everything worn, consumed, or carried for use in a tactical environment and that contributes to training" (Marine Corps Studies and Analysis Division, December 2004).

Key to evaluating the effectiveness of the MERS in an urban environment is the evaluation of the MERS as a system; the total effect of the physical assets of the MERS

must be taken into consideration. A base scenario
consisting of a MERS conducting a combat patrol in a small
neighborhood of Fallujah (750 meters x 800 meters) was
modeled utilizing the agent-based Map-Aware Non-Uniform
Automata (MANA) model (Figure 1). Critical areas of
effectiveness explored were Lethality, Survivability, and
Situational Awareness (SA) (Command and Control (C2)).

Figure 1.   An aerial view of the modeled terrain (left)
             and the MANA translated map (right). (Best
             viewed in color)

In order to explore as many different levels of these
factors as possible, Marine Corps data farming (utilizing a
Nearly-Orthogonal Latin Hypercube) and supercomputing
capabilities were called upon. This led to a final
evaluation design of experiment consisting of 66 separate
factor level combinations, allowing a wide range of levels
to be explored in order to capture the most important ones.

In analysis of the scenario, the most interesting and
important result is that the MERS must be evaluated as a
system; the interactions between factors identify the
effects that are gained or lost in the presence of each
other. Two factors are identified as the most significant

in affecting all of the measures of effectiveness (MOEs); *survivability* and *lethality*. These two factors show the highest significance in all of the linear regressions and classification and regression trees.

More insights are:

- **Mass** (the number of agents in friendly or enemy units) is still significant. Mass equates to more rifles in the fight, vice more targets on the ground. Larger forces enable the MERS to kill more enemy and enable the enemy to reduce the ability of the MERS to accomplish the mission.

- **Situational Awareness** is a double edged sword. In MANA, SA was modeled as the sharing of contact detection/classification in the MERS. As each agent detected and shared information on contacts, fusion of two MERS agents detecting the same enemy agent allowed for 'perfect' SA management. Nevertheless, multiple detections and fusions necessitates the model spend time prosecuting the current contacts vice detecting new ones. This is akin to the real world problem of information overload. A Marine that is trying to process too much information is a Marine that is not in the fight, which can end up as a dead Marine.

Many of these insights appeal to the intuitiveness of Marines; given a survivable and lethal squad, the mission can be accomplished with high probability. The research

has quantified concepts that are held true by Marines today. This in turn allows further analysis to be conducted, utilizing this new tool, in evaluation of the best course of action to ensure that our Marines are the best equipped and trained, most survivable and lethal force the enemy will ever face.

I. INTRODUCTION

A. RESEARCH PLAN OF ATTACK

1. Objectives of Research

The primary objective of this research is to identify the key parameters influencing the effectiveness of the Marine Expeditionary Rifle Squad (MERS). As an infantry officer, the author is well versed in traditional tactics, techniques, and procedures (TTPs), as well as current threat TTPs. The MERS concept represents a potential for increasing the overall capabilities of the infantryman. Evaluation of the MERS concept will be accomplished through the analysis of a MERS engaged in urban combat using an agent-based simulation. An important aspect of the analysis will be to take into consideration the interactions between different parameters and different levels of each parameter. Doing so will ensure that the squad is evaluated as an integrated system, the ultimate goal of the MERS concept.

2. Use of Research

This study presents information on techniques for better representing combatants in combat models, especially small unit land combat. Agent-based modeling offers a relatively user friendly capability for analysis. An added benefit will be to identify a suitable tool for use by the Marine Corps Systems Command in evaluating potential weapons and equipment for procurement. Thorough analysis, utilizing the correct tools, will provide a sounding board for decisions on equipping our fighting forces.

3. Flow of Thesis

The thesis begins with an introduction that discusses the environment of conflict in the world today, followed by discussion of the simulation used, a scenario overview, and a discussion of the measures of effectiveness. It continues with a detailed discussion of the designs of experiment, the parameter settings used for data farming, and the final set of parameter values that were found to produce the most desirable results. A detailed statistical and analytical evaluation utilizing traditional regression techniques, as well as regression trees (or partitions) are used to highlight interesting findings. Finally, further courses of study are suggested in order to continue the analysis of small unit combat.

B. BACKGROUND

1. Mitigating New Threats in the Global War on Terrorism

The Global War on Terrorism has introduced the United States to new threats that present new capabilities and that are dedicated to destroying our way of life. Terror organizations have demonstrated the ability to utilize varying and adaptive tactics to inflict mental and physical casualties on the United States and its allies.

> The U.S. is engaged in a long-term global war of ideas, values and interests, waged against an ill defined and ever changing enemy. This enemy is adaptive, committed to his cause, technologically and psychologically savvy, and thoroughly ruthless. (Marine Corps Future Operations Division, December 2004)

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In an effort to mitigate the new threats, the United States Armed Forces have begun to evaluate and employ organizational structures, and tactics, techniques, and procedures that vary from traditional concepts. Once again, the infantryman has become the best solution to combat new threats that have applied tactics that reduce the capabilities of modern American combat power. Ensuring the man on the ground is prepared to face the enemy will lead the United States to victory in the Global War on Terrorism. "On today's battlefield, with irregular warfare, victory quite often goes to those individuals who can do something faster, working inside the enemy's decision cycle" (Hagee, May 2005).

2. Distributed Operations Defined

The United States Marine Corps has seen the concept of Distributed Operations (DO) rise to the top of potentially effective options.

> [In order] to provide the capabilities Joint Force Commanders will need to meet the wide spectrum of challenges that our nation will face in the 21st Century… [w]e will continue to rely on our fundamental tenants of Expeditionary Maneuver Warfare and Combined-Arms Air-Ground Task Forces. We will enhance and expand these capabilities through the aggressive implementation of Sea-Basing and Distributed Operations. (Hagee, April 2005)

Distributed Operations are "those military operations which entail the intelligence driven, decentralized application of networked and fully integrated combined arms maneuver forces, alternatively dispersing and aggregating over extended distances, to observe, target, influence, dislocate, defeat, or destroy traditional and non-

traditional threats" (Marine Corps Future Operations Division, December 2004). The Marine Corps believes DO "greatly expands current force capabilities in joint, combined, and interagency operations across the full range of military operations" (Marine Corps Future Operations Division, December 2004).

> Distributed forces present complexity to the enemy… Complexity induces confusion and ambiguity in the opponent and produces a competitive advantage for our forces… The adversary is further disrupted by combined arms or multidimensional attacks. (Schmiddle and Hoffman, Sept 2004)

DO contains several key characterizations; "Marine centric, decentralization, complexity, multi-dimensionality, simultaneity, adaptability, and continuous pressure" (Marine Corps Future Operations Division, December 2004). DO will allow the Marine Corps to adapt to new threats and leverage current capabilities to more effectively engage the enemy. In Distributed Operations, the infantry squad will serve as the base unit, and its capabilities must reflect the need of increased decentralization and self-sustainability (in a combat and logistical sense).

> Implementation of Distributed Operations as an extension of maneuver warfare will require a focus on enhanced small units: more autonomous, more lethal, and better able to operate across the full spectrum of operations. This will require investing in the technologies and training that will provide individual communications, tactical mobility, and networked intelligence down to the squad level. Our logistics and fires capabilities must be adaptive and scalable in order to support these small units, whether dispersed across the battle space

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or aggregated for larger operations. (Hagee, April 2005)

Realizing the need for an infantry squad with improved capabilities, the concept of the Marine Expeditionary Rifle Squad was developed.

3. The Marine Expeditionary Rifle Squad in Support of Distributed Operations

The Marine Expeditionary Rifle Squad (MERS) is "that distributed close combat fighting capability embodied in the Marines Corps Infantry, to include everything worn, consumed, or carried for use in a tactical environment and that contributes to training" (Marine Corps Studies and Analysis Division, December 2004). The MERS concept is to be used to help identify capabilities that are important for the conduct of Distributed Operations. The goal of the MERS concept is to "man, train, organize, provide current doctrine, lead and equip the Marine Infantry Rifle Squad in an integrated, holistic and systematic fashion that increases the overall fighting ability of the entire unit across the spectrum of its missions" (Carlson, April 2004). These capabilities are primarily physical and tangible in nature; an improved weapon, lighter body armor, etc. The Marine Corps is evaluating current production options, as well as procurement of future systems. The MERS will retain all of the current functionality of a traditional Marine infantry squad. The new integrated concept will facilitate the additive capabilities of Distributed Operations.

4. The Squad as a System

An important aspect of the MERS concept is the idea that the squad be treated as a system in the evaluation of its performance and mission accomplishment. This allows a better evaluation of the combined effects of the introduction of new weapons and equipment; the unit's effectiveness is better represented for evaluation rather than aggregating the individual members of the squad's effectiveness. Current Marine Corps doctrine and table of organization (T/O) specifies the framework for a standard Marine infantry squad (Figure 1):

- 1 Squad Leader

- 3 Fire Team Leaders

- 3 Automatic Riflemen

- 3 Assistant Automatic Riflemen

- 3 Riflemen

All Marines are similarly equipped (table of equipment (T/E)) based on their billet assignment. This allows for ease of aggregation for the evaluation of the squad's performance.
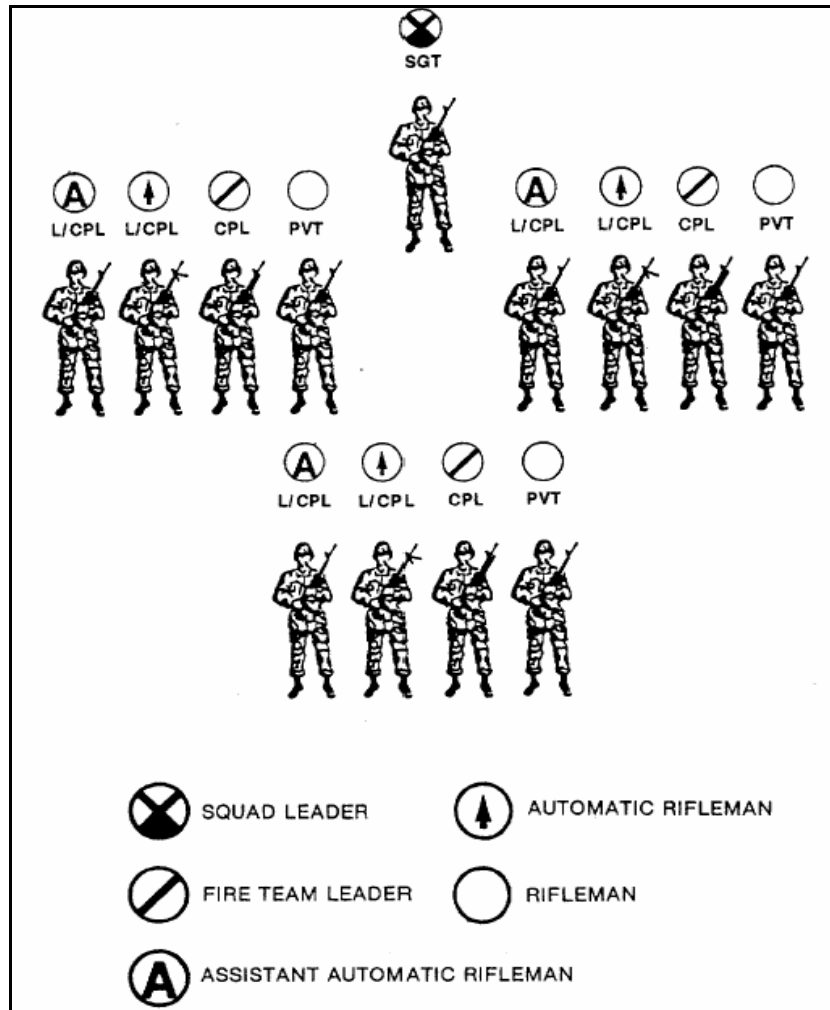
Figure 1.   Current Marine Rifle Squad organization (T/O)
             (Fleet Marine Force Manual 6-5)

        The standard tactics used to close with and destroy
the enemy revolve around the principle of fire and
maneuver. Fire and maneuver consists of a group of Marines
engaging the enemy, using various weapons as the situation
dictates, in order to gain combined arms effects, while
another group moves to close with the enemy. Fire and
maneuver consists of a specified sub-unit (e.g., Fire Team)
fixing or suppressing the enemy while the other units
maneuver to close with the enemy.

The MERS will be evaluated based on the same T/O as the current structure, but will employ varied tactics, techniques, and procedures in order to support Distributed Operations. This may result in the MERS operating aggregated, disaggregated, or reinforced (with additional external assets, e.g., Civil Affairs Teams).

In support of Distributed Operations, the MERS may be required to conduct 'swarming' tactics in which it will maneuver asymmetrically with other networked MERS in order to disrupt, fix, and destroy the enemy. It may be required to aggregate into a larger unit in order to apply a massed force at a decisive point against a fixed enemy. Likewise, it may just as easily be required to operate disaggregated, providing surveillance of critical areas and threats. All of these additive tactics require a more capable infantry squad.

II. MODEL, SCENARIOS, AND MEASURES

In order to answer research questions, analysts have many tools at their disposal. An effective set of tools are combat models, particularly agent-based models. As with any model, scenarios must be well developed and parameter settings must be understandable and practical. Finally, the analysis cannot begin until measures are developed that can provide insights into the results. The combination of these three things lays the foundation for quality analysis.

A.   AGENT-BASED MODELING: MAP-AWARE NON-UNIFORM AUTOMATA (MANA)

The Map-Aware Non-Uniform Automata (MANA) is an agent-based model developed by David Galligan, Michael Lauren, and Mark Anderson of the New Zealand Defence Force (MANA User Manual, 2004). The model was developed to overcome shortfalls of past complex adaptive system (CAS) and agent-based models. In the past, many of these models were dismissed because they did not have a strongly physics-based approach to modeling. The developers of MANA believe differently:

> The history of physics has been characterised by the search for systems simple enough to be able to be described with a high degree of accuracy by mathematical equations. Isaac Newton's laws of motion are an example. Although extremely accurate at predicting, for example, the path and distance traveled by a heavy projectile, they cannot in general be relied on. If the projectile is light, it then becomes subject to a far greater degree to the viscous drag of the atmosphere, which makes the original calculations

invalid. These equations cannot with complete generality be simply or easily "corrected" for the action of the drag. The reason is that the interaction between the viscous atmosphere and the projectile is just too complicated and dependent on too many variables (particularly if the projectile is light and has irregular shape, like a feather), not to mention that the atmosphere itself is unpredictable and turbulent. This simple example illustrates a powerful point: the world is far more complicated than Newton's equations. To this day, there exists no set of equations that can with absolute certainty predict the evolution of the vast majority of phenomena we see in everyday life for any significant period into the future. Therefore, to rely on models built "on a bedrock of physics" is to deceive ourselves. It is a myth that a more detailed model is necessarily a better model, because it is impossible to capture accurately every aspect of nature. In fact, the more detailed a model is, the more obscure its workings, a problem that is compounded if the user is not the model designer. (MANA User Manual)

The author expended much effort in order to select the best tool to evaluate MERS capabilities. This included evaluating other agent-based models (Pythagoras and Einstein), as well as an on-site evaluation of the next generation physics-based model, Combat XXI. In the end, there was no competition between MANA and the other models. Each model has nice features, but none possess the complete package that MANA provides.

A modeler can take advantage of MANA's easy setup and short run times to explore a vast space of parameter values. Combining this with designs of experiments utilizing nearly-orthogonal Latin hypercubes produces results that allow magnitudes more parameters to be evaluated than is feasible with other legacy combat simulations.

MANA has three capabilities that set it apart from other models:

- **The agents are "map-aware"**; they know where they are in relation to things around them and remember information such as where an enemy contact last took place.

- **The model is events-based**; occurrences of an event, such as detection, trigger a state change that can have state-specific behaviors and characteristics.

- **The model is user friendly**; it requires minimal experience to begin use and is flexible enough to create scenarios and gain insights in a fraction of the time needed for other models.

As an agent-based model, an important capability is to model behavioral interactions between agents. This allows complex relationships to be well modeled. This is strongest in small unit combat, an area that has traditionally been difficult to model utilizing larger physics-based models. The author established a well defined personality for each subunit modeled in MANA through personal experience and discussion with military peers. After the personalities are defined, the user has the ability to tailor the environment, mission, goals, etc.

to evaluate multiple options. With the correctly modeled personality, the tactics and relationship rules will be applicable to any scenario, in whole or with minor adjustments.

B.   SCENARIO OVERVIEW

1.   The Story

Current combat operations have highlighted the need for highly-trained, well-equipped, decentralized small units that can adapt quickly to an ever changing situation. These units need to be able to employ lethal organic fires as well as direct precision inorganic assets. They need to be able to overpower enemy forces that may outnumber them and exploit fleeting opportunities as they arise.

This type of combat was indicative of Operation Al Fajr, the Battle of Fallujah, which took place during Operation Iraqi Freedom. Due to the urban environment and disaggregated enemy hiding within it, United States and coalition forces were reduced to small unit combat. Given this characterization, the author suggests that Operation Al Fajr is an example where both concepts of MERS and DO may have been well employed. "Depending on the sector [in Fallujah] searched, the individual squad engaged in 8 to 24 close quarters firefights over an 8-day period, and none flinched"(West, July 2005).

The base scenario modeled revolves around a MERS conducting a combat patrol in an urban environment (a small neighborhood of Fallujah (Figure 2) (750 meters x 800 meters)), a common occurrence in Operation Al Fajr.

Figure 2.   Overhead imagery of modeled terrain

The squad is modeled as a single unit that has intra-squad communication and a shared situational awareness. There is no external input from inorganic assets, such as reconnaissance teams, unmanned aerial vehicles (UAVs), etc.

Important to analysis of the MERS is their ability to utilize inorganic fires (artillery, close air support, etc.) in order to accomplish the mission. A scenario utilizing external support, modeled as an indirect fire unit, was also briefly explored, but requires more in depth analysis.

There are several key factors that are of interest to the evaluation of the MERS; command and control (C2), lethality, mobility, survivability, sustainability, and training (Figure 3). The MERS concept looks to increase the abilities of the Marine Rifle Squad in all of these areas.
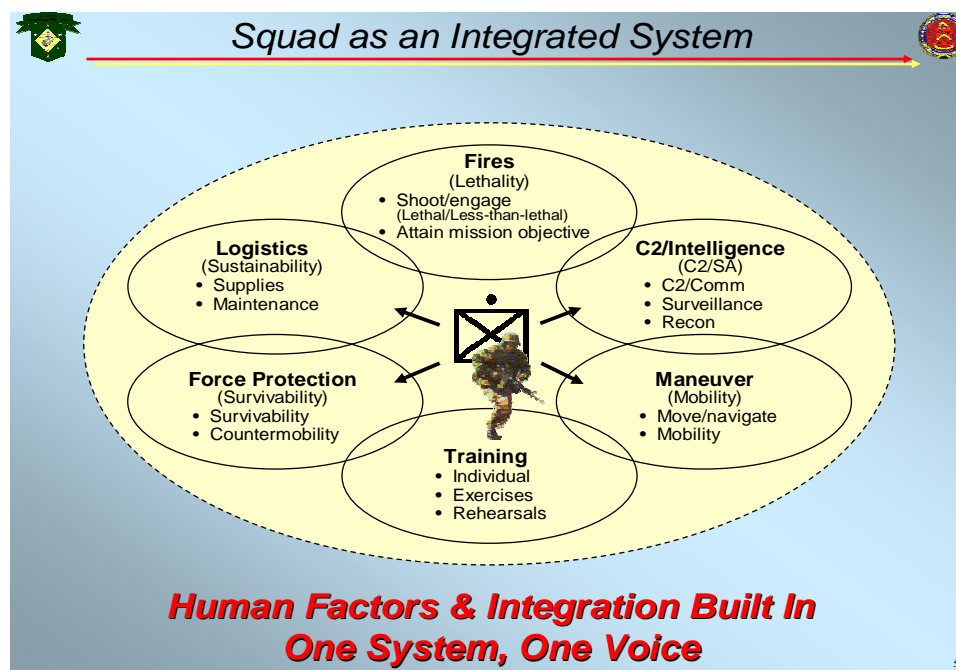
Figure 3.   The six factors that compose the squad as an integrated system concept. (Carlson, April 2004)

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2. Scope

This thesis explores the outcomes of increasing capabilities, decreasing limitations, and the trade-offs between them, in the specified scenario. This is accomplished by utilization of agent-based modeling in order to identify the key factors that affect the overall effectiveness of the Marine Expeditionary Rifle Squad in support of Distributed Operations in urban operations. Critical areas of evaluation to be explored are Lethality, Survivability, and Situational Awareness (SA) (C2). Along with evaluation of the aforementioned critical areas is the development of Measures of Effectiveness (MOEs) in order to continue to improve the analysis of the MERS.

a. Force Size

As evident by the title, the focus of this work is at the squad level (9 to 21 Marines, dependant on attachments and detachments). That being said, based on the concept that larger scale combat is an aggregation of smaller scale combat, this work may be applicable to larger units. As an infantryman, the author has long understood that in order to have effective and efficient platoons and companies, the squads must be trained to the highest of standards. Modeling and analysis of units above squad level is feasible, once the behaviors and characteristics are well defined at the squad level (see Chapter II, Section A. Agent-Based Modeling).

The enemy force is based on a similarly sized unit to the Marine unit. An important area of evaluation is the ability of the MERS to deal with a much larger enemy unit than their squad (75-100% larger than the MERS; this situation is explored through data farming).

b. *Force Compositions*

Both the MERS and the enemy unit are similarly equipped as light infantry forces (essentially restricted to the equipment that can be physically carried by the individual). This keeps a level playing field baseline for evaluation.

The traditional Marine infantry squad has an organization based on three fire teams (Figure 1). The modeled MERS is based on this concept. The enemy forces are randomly distributed between 3 pre-selected positions on the MERS' patrol route (Figure 4). This results in the MERS randomly engaging a large enemy concentration or smaller enemy concentrations spread out over the battle space.

Figure 4.   The distribution of enemy forces in the scenario. The top picture shows an evenly distributed enemy. The bottom picture shows larger concentrations of enemy (terrain is 750 x 800 meters). (Best viewed in color)

c. *Force Capabilities*

As stated in Force Compositions, both friendly and enemy forces are considered to be light infantry. This limits their capabilities to man-portable equipment. They are both equipped with direct-fire kinetic-energy weapons (rifles). The only organic sensor assets can be considered to be optical (based on line-of-sight (LOS), e.g., human vision or vision assistance tools such as a rifle combat optic (RCO)). The MERS has the capability to maintain intra-squad communications, which increases their SA. The enemy force is restricted to agent SA. The forces are foot-mobile with no external support (mobility or fires). Survivability, or the ability to defeat enemy fires, either through direct factors (anti-penetration) or indirect (ability to not be detected and engaged), is implicitly modeled through a combination of model specific parameters (there is no well defined "body armor" factor in MANA).

d. **Terrain**

The terrain chosen for this modeling and analysis is an urban neighborhood (akin to a suburb) of Fallujah, Iraq (Figure 2). The area is characterized by one- and two-story, mud-brick constructed houses and shops. This type of environment is one that has begun to dominate conflicts in the world today.

The buildings are primarily built flush with the streets; the only open areas around the buildings are small walled-in courtyards. This became a hampering point during Operation Al Fajr. Friendly forces were forced to maneuver the streets and breach the walls that lined them in order to move between them (Figure 5).

Figure 5.   Marines take up positions along a narrow street in Fallujah. (Photo Credit: Luis Sinco, Los Angeles Times)

Another key aspect of the terrain is the presence of micro-terrain, the natural and man-made clutter that fills the areas around larger terrain features. In the infantry, a common saying is that six inches can save your life; six inches of micro-terrain can keep a bullet from reaching you. Fallujah had been sufficiently rubbled by the time of the attack during OIF (Figure 6). This left many piles of bricks, trash, etc. that could be utilized for cover and concealment.

Figure 6.   1st Division Marines on the move in western
             Fallujah. (photo credit Associated Press]

        This is modeled in MANA through the use of the
elevation map feature. By introducing randomly distributed
pixels of white space (translated in MANA as infinite
elevation), the effect of added noise can be introduced
into the calculation of LOS (Figure 7).

Figure 7.   Elevation map utilized to add noise to LOS calculations in order to simulate rubble; white space is evaluated as infinite elevation in MANA; therefore, if there is white space between two agents, they will not detect one another. (Best viewed in color)

MANA utilizes different color combinations to delineate restrictions on LOS, movement rates, and elevation. MANA evaluates the percentage associated with each color hue during the prosecution of detection and classification; the value affects the probability of each. In this model, a gray feature represents terrain (buildings) that is impassable to movement and LOS; that is, the agent cannot move through walls and they provide perfect cover and concealment. The olive green hue represents rubbled areas that result in reduced movement speeds and added concealment and cover (60% movement rate, 20% cover, and 50% concealment—all compared to zero

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restricted terrain). The regular green color represents semi-rubbled streets (80% movement rate, 10% cover, and 20% concealment). These effects are evaluated each time step (i.e., every two seconds).

3. Modeling Limitations

MANA is an excellent tool for modeling complex adaptive systems (CAS), especially small unit combat (see II. Model, Scenarios, and Measures, A. Agent-Based Modeling: Map-Aware Non-uniform Automata). Of course, it is not without its limitations. The biggest limitation in modeling revolves around the ability for the units to provide standard tactical responses (in the form of maneuver and fire) to situations. For example; when confronted with an enemy force that is engaging the front of a column formation, traditional tactics would dictate the rear sub-units to flank and provide suppressive fires on the enemy in order to allow the engaged portion of the column to maneuver to cover or against the enemy. In MANA, when a part of the unit is engaged, the rest of the agents become aware of the situational map and begin to maneuver based on their predetermined behaviors. This may result in the aforementioned behavior of flanking and suppressing, or it may result in some subunits maneuvering past the enemy in order to continue on the mission.

Though this may be listed as a limitation, it is truly a desirable effect because it may result in the observance of emergent behavior by the agents—that is, the agents may recognize the situation and find a solution to the problem, based on the pre-defined behaviors (see Chapter IV, B. Insights, 4. Emergent Behavior).

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Another set of limitations lies in the actual settings of the model. It may be desirable in some cases to have the ability to "dial in" a value, say the anti-penetration capabilities of body armor, for example. Instead, the modeler is forced to utilize several surrogate methods to capture the desired measures; for example, enemy PK as a surrogate for friendly body armor effectiveness. This allows MANA to be applied to much broader analyses rather than only being able to model combat.

MANA utilizes a grey scale in order to define elevation. The author modeled elevation, or the effects of, by the use of controlling movement, cover, and concealment rates. This approach allowed for more control in the scenario. This does not allow an agent to occupy an elevation higher than the other agents.

4. Modeling Assumptions

In the evaluation of the proper tool to utilize, the author was subject to many discussions on the topic that agent-based models are subject to too many assumptions. As with any model, assumptions are necessary.

The key assumptions in the scenario modeled revolve around an aggregation and simplification of capabilities and limitations. For all agents in the model, they are considered to be similarly equipped with a single, direct-fire, kinetic-energy weapon (e.g., a rifle). They have a single, LOS-based, optical sensor (e.g., human vision or a vision assistance tool). The time step of the model is 2 seconds per time step. Based on an assumed average two hour mission, the average seconds would be 7200. In order

to allow for longer missions, the author divided 7200 by 2, converting to an average number of time steps of 3600.

The ability of agents to be detected (stealth factor in MANA) is utilized several ways. When an agent is fired upon, they have the ability to assume a position that presents less of a target to their adversary (e.g., the prone). This is modeled through increasing their stealth value. Stealth is also used to capture the ability of agents to remain undetected overall. This may be analyzed as increased training that allows for agents to move with less probability of detection or a lower signature due to better camouflage. The important fact is weather or not stealth as a factor increases the overall effectiveness of the agents. If stealth does increase effectiveness, the question becomes how best to do this given the various options.

The max effective range of engagement in the model is assumed to be 300 meters. This is more than enough distance, especially in an urban environment. The Probability of Kill (PK) is varied within this range, with initial settings of 0.3, and is considered to be zero outside of 300 meters.

The model makes use of Detection Range, Classification Range, and Probability of Classification (PC) in a unique way in order to allow easier data farming. The Detection range is 1000 meters, allowing the agents to 'view' the entire battle space and the Classification Range is 100 meters with an accompanying PC. This is a practical assumption in urban operations. The initial PC is set to be 0.5 from 0 to 100 meters, and 0 beyond 100 meters. In this arrangement, PC is dependant on detection; it may be

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viewed as probability to classify given detection is 0.5 from 0 to 100 meters. In the author's experience, detections are much less difficult than classification, especially in an urban environment.

The final assumption of the model deals with the time that a contact stays active in the agent's/squad's SA map. It is assumed that after 150 time steps (150 time steps = 5 minutes), the contact will fall off the SA map. So, based on the fact that the clock starts each time there is a contact, if a contact disappears from the SA map after 5 minutes, the squad has most likely moved beyond the influence of that contact and it is insignificant to their mission.

C.   MEASURES

1.   Overview

One of the goals of this research is to identify potential measures of effectiveness for use in modeling the MERS and DO overall. Traditional measures have dealt with odd calculations and exact values; speed of completion, increased contact gains, less friendly casualties, etc. While these are important and useful values, evaluating more general measures, such as the ability of the modeled unit to accomplish the mission and to kill enemy forces while protecting friendly forces may be more important—especially in the agent-based simulation environment. Often, various settings and values used in agent simulations do not translate well to the real world. The analysis of the results (e.g., trends) is more important than the specified numbers.

MOEs also need to appeal to the warfighting intuitiveness in all Marines. They need to measure the fact that Marines are concerned with combat; killing the enemy, protecting Marines' lives, and accomplishing the mission. Ensuring that these tenets are followed allows for a better evaluation and for the simulation to gain validity in the eyes of warfighters.

2.   Measures Utilized

a.   Exchange Ratio

The Exchange Ratio is calculated as ratio of the proportion of casualties (number of casualties divided by the number of agents) for friendly and enemy agents (Figure 8).

$$\frac{proportionEnemyCasualties}{proportionFriendlyCasualties}$$

Figure 8.   Exchange Ratio calculation.

The exchange ratio allows for a practical evaluation of the trade-off between friendly and enemy forces. Large values of the exchange ratio are desirable (high enemy casualties divided by low friendly casualties).

b.   Probability (Friendly Mission Completion)

Mission completion is reached only if two conditions are met; (1) the percentage of friendly

casualties is below one-third and (2) the friendly unit reaches the goal. In MANA, if any member of the squad reaches the goal it is recorded as a success. In this analysis, only a unit that is still combat effective (two-thirds intact) when the goal is reached is counted as a success. This negates the chance that a lone survivor reaches the goal and the mission is recorded as a success.

c. Proportion Friendly and Proportion Enemy Casualties

These two measures are examples of exact values that are of interest in the analysis. The proportion of forces that result in casualties is a metric that translates well into an easily evaluated number. It also falls into the category of measures that take a macro view of the simulation, desirable in the analysis.

d. Time to Mission Completion

This measure is used to evaluate the increased or decreased effectiveness of the MERS. If one assumes that an increase in capabilities of the MERS should relate to a decrease in mission length, then the time to mission completion becomes a viable measure.

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III. DESIGN AND METHODOLOGY

A.   DESIGN OF EXPERIMENT

The parameters selected to evaluate are based on the concept that the MERS will provide increased effectiveness through better weapons, communication equipment, situational awareness, etc. As with many simulations, there are not always well defined real-world-to-model parameters. This requires simulation parameters to be defined in order to provide insights to the modeling question.

It is also important to explore a wide range of values in order to have a better chance of capturing significant ranges. This need requires good designs of experiments and utilization of supercomputer facilities in order to data farm.

1.   Parameters Explored

a.   *MERS_stealth (Survivability)*

This is the single step probability of no detection by an enemy within detection range. There is a cumulative probability effect; that is, the more opportunities the enemy has to detect an agent, the more likely it is that he will. The parameter may be varied from 0 to 100, but is only varied from 10 to 90 (allowing for a realistic range of concealment).

b.   *MERS_numAgents*

The MERS concept, in support of DO, proposes that units will be tasked organized to fit missions. This parameter is based on the standard 13 man squad, but varied

based on the possibility of detaching a 4 man team, or attaching up to two 4 man teams (resulting in anywhere from 9 to 21 Marines in the squad).

c.   Enemy_numAgents

It is important that the MERS be able to defeat enemy forces that range from small units (5 agents) to larger units (20 agents). The MERS must also be able to defeat enemy units that are large compared to the number of agents in the MERS.

d.   MERS_commsDelay (Situational Awareness (C2))

This is the intra-squad delay of information sharing or situational awareness of the agents in the squad, by time step. It is varied from zero delay to a five minute delay; an enormous value given that a typical squad would only have a footprint of 100 meters x 100 meters on the ground in urban terrain, but allows for full evaluation of the importance of this parameter.

e.   MERS_taken_shot_duration

This is the state duration utilized to model time between shots fired at targets. This technique is used because it is much simpler and more intuitive than the MANA variable of "firing rate".

This parameter may be used as a surrogate for several sources of improved effectiveness. It may be argued that the improved training that the MERS and DO units receive leads to the ability of the Marine to engage more targets at a faster rate. Improved equipment that allows for better target selection and engagement may also

be surrogated by this parameter. The range of evaluation
is from 2 seconds to 90 seconds. Again, a broad range of
possibilities is explored.

f. MERS_shot_at_duration

This is the state duration of the state entered
when an individual MERS agent is shot at by an enemy agent.
It models the ability of a Marine to get back in the fight.
As is the case with the previous parameter, this parameter
may be used as a surrogate for improved training or
equipment. The range of evaluation is from 30 seconds to 5
minutes.

g. MERS_squad_shot_at_duration

This is the state duration when a member of squad
is fired upon. It models the squad's reaction to enemy
fire and ability to get back into action. This parameter
can surrogate the common SA of the squad, improved
training, or improved weapons. The range of evaluation is
from 30 seconds to 5 minutes.

h. Enemy_PK (Survivability)

This is the single shot Probability of Hit/Kill
(SSPK). In this model, it is used as a surrogate for MERS
survivability; lower enemy PK = higher MERS survivability.
It can be used to highlight the need for better body armor,
protection, etc., or the need for a better ability of the
squad to avoid being engaged by the enemy (through
training, tactics, etc.).

i.   MERS_PK (Lethality)

This is modeled as a typical SSPK. It should be noted that a real-world-to-model translation of this PK is not a practical thing; it is much better to evaluate the importance of lethality in general.

j.   MERS_Pdet_class (Situational Awareness (C2))

This is the Probability of Detection and Classification, which is a simultaneous event in this model. This parameter may be viewed as a surrogate for sensor capabilities in whole. In the scenario, detection occurs at an infinite range, given a LOS, and classification (friend, enemy, neutral) may occur at less than 100 meters. In MANA, only PC is modified. This arrangement allows classification to be surrogated for detection.

2.   Nearly-Orthogonal Latin Hypercubes

Nearly-Orthogonal Latin Hypercubes (NOLH) are a method of designing the parameter combinations and values in order to gain nearly orthogonal correlations between parameters that are varied (Cioppa, 2002). This allows the evaluation of main effects and interactions of parameters. The greatest benefit of the NOLH is that the necessary number of excursions (different parameter combinations) needed in order to properly fill the parameter space is orders of magnitude smaller than traditional designs, such as a dense grid. This in turn allows more replications to be executed, with varied random seeds, in order to add to the statistical significance of the analysis.

Based on the 10 parameters evaluated, only 33 excursions are needed to gain an adequate space filling design. In order to increase the fidelity of the results, 66 excursions are used, with 30 replications at each excursion (Appendix C). The data is then summarized as means for each excursion and analytical techniques are applied to see the relationships between the parameters explored and the MOEs.

3. Data Farming and Supercomputing

Paramount to identifying key factors in the effectiveness of the MERS is the utilization of Data Farming. This concept, hand-in-hand with supercomputing capabilities, allows for wide ranges of parameter values to be explored. This allows them to be narrowed down to smaller sets of influential values. Identifying influential ranges of parameter values then allows for a better application of the NOLH design in order to identify important effects and interactions. Data Farming prepares the ground in order to grow interesting outcomes.

B. METHODOLOGY INSIGHTS

In developing a good set of behaviors and a realistic scenario, many scenario revisions were utilized. With each revision, the author became more proficient with the tools available and with creating a scenario that allowed for the best evaluation of the capabilities of the MERS. In this process, several insights were gained. First, initial scenario executions necessitated unrealistically low values for PK (based on the desire to at least provide some real-world-to-model translation). These early scenarios

utilized very basic behavioral rules and agent interactions. They were not much more than establishing a goal and pressing go. As the behaviors became better developed, and a detailed events-based evaluation was conducted on agent-interactions (with complimentary state changes), the need arose for a more realistic modeling of PK (resulting in a 30% PK at 300 meters as a baseline). This was a very interesting outcome. Overall, as the model became more realistic the values of parameters gravitated to reality as well.

Second, the development of adequate surrogate measures was vital to gaining insights into the modeling of small unit combat. As with any model, perfect real-world-to-model translations of values are difficult to capture. The use of surrogates enables the analyst to gain insights nevertheless (see example, III. Design, Methodology, and Data Analysis, A. Design of Experiment, 2. Parameters Explored, h. Enemy_PK).

Last, agent-based models pose new challenges in balancing emergent behaviors and adequate scripting of the scenario. The analyst must be willing to accept less control over the model (e.g., routes and engagement criteria) in order to gain better insights into more chaotic situations.

IV. DATA ANALYSIS

A. OVERVIEW

In conducting the analysis of the results, the author focused on techniques that would help identify overarching statistical trends. This is primarily accomplished through the use of regression trees, or partitions. The statistical package JMP 5.1 discusses partition as follows:

> The **Partition** platform recursively partitions data according to a relationship between the *X* and *Y* values, creating a tree of partitions. Variations of this technique go by many names and brand names: decision trees, CART^{TM}, CHAID^{TM}, C4.5, C5, and others. The technique is often taught as a data mining technique, because
>
> - it is good for exploring relationships without having a good prior model
>
> - it handles large problems easily, and
>
> - the results are very interpretable.
>
> The factor columns (*X*'s) can be either continuous or categorical (nominal or ordinal). If an *X* is continuous, then the splits (partitions) are created by a *cutting value*. The sample is divided into values below and above this cutting value. If the *X* is categorical, then the sample is divided into two groups of levels.
>
> The response column (*Y*) can also be either continuous or categorical (nominal or ordinal). If *Y* is continuous, then the platform fits means, and creates splits which most significantly separate the means by examining the sums of squares due to the means differences. If *Y* is categorical, then the response rates (the estimated probability for each response level) become the fitted value, and the most significant split is determined by the largest likelihood-

ratio chi-square statistic. In either case, the
split is chosen to maximize the difference in the
responses between the two branches of the split.
(JMP Start Statistics, 3rd Edition)

The ability of the partition to be interpretable is
most important.   This allows for the modeler to easily
explain the results to decision makers.

Traditional Least Squared Error (LSE) Regression is
used to compliment the partition.   Akaike's Information
Criteria (AIC) is used to select influential parameters,
followed by the LSE regression.   AIC is a stepwise
heuristic that identifies the best values through the
computation of the AIC value (Figure 9).

$$AIC = n \ln\left(\frac{SSE}{n}\right) + 2p$$

Figure 9.   Calculation of AIC statistic. SSE is the sum of
             squared errors between the observed and
             predicted values, n is the number of
             observations, and p is the number of model
             parameters including the intercept. The model
             with the lowest AIC is considered best. (JMP
             Start Statistics, 3rd Edition)

B.   METHODOLOGY EXAMPLE: PROPORTION FRIENDLY CASUALTIES
A good example of the methodology utilized is with the
MOE of Proportion of Friendly Casualties.   All of the
parameters (main effects), two-way interactions, and
quadratic terms are entered into the Stepwise Regression

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procedure.   The threshold for deciding whether a term under investigation is included or removed from the model is set at the 0.10 significance level.   The goal is to create a model that produces the best R Squared value. R Squared is the percent of variation the model explains, or how well the model fits; the higher the better.   The Stepwise algorithm evaluates whether or not including or removing the term improves the R Squared value, based on the AIC statistic. Once the Stepwise algorithm has reached the best R Squared possible, the analyst has the option of creating a model for evaluation with LSE Regression that contains all of the recommended terms from the Stepwise Regression or a user-defined model.

The full model explored after the Stepwise Regression procedure is a 14 parameter model that displays many interactions (Figure 10).

$$propFriendly\,Casualties = 0.813 + 0.022(Enemy\_numAgents)$$
$$- 0.019(MERS\_numAgents) + 0.00008(survivability)$$
$$- 0.00008(lethality) - 0.00004(sensor\_capability)$$
$$- 0.0014(stealth) + 0.003(Enemy\_numAgents * stealth)$$
$$- 0.0000005(sensor\_capability * stealth)$$
$$- 0.0031(Enemy\_numAgents)^2 + 0.0022(MERS\_numAgents)^2$$
$$- 0.00000001(survivability)^2 + 0.000000006(lethality)^2$$
$$+ 0.000000007(sensor\_capability)^2$$

Figure 10.   Model equation for full 14 parameter model of Proportion of Friendly Casualties.   Note the multiple interaction terms included. The model R Squared value is 0.9485.

The overall fit of the model is 0.9485 (Table 1).

Summary of Fit

RSquare	0.948545
RSquare Adj	0.935681
Root Mean Square Error	0.076481
Mean of Response	0.614596
Observations (or Sum Wgts)	66

Table 1.   Table displays the fit of the full model.

The associated parameter estimates and significance levels are seen below (Table 2).

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.812676	0.069167	11.75	<.0001
Enemy_numAgents	0.0221447	0.002397	9.24	<.0001
MERS_numAgents	-0.019179	0.002617	-7.33	<.0001
Enemy_PK	0.0000881	0.000005	19.55	<.0001
MERS_PK	-0.000075	0.000004	-16.66	<.0001
MERS_PD	-0.000036	0.000004	-8.01	<.0001
MERS_stealth	-0.001423	0.000453	-3.14	0.0028
(Enemy_numAgents-12.5152)*(MERS_stealth-51.2121)	0.0003225	0.00011	2.92	0.0051
(MERS_PD-4509.09)*(MERS_stealth-51.2121)	-5.114e-7	2.353e-7	-2.17	0.0344
(Enemy_numAgents-12.5152)*(Enemy_numAgents-12.5152)	-0.003155	0.000767	-4.11	0.0001
(MERS_numAgents-15.0606)*(MERS_numAgents-15.0606)	0.0022467	0.000934	2.41	0.0197
(Enemy_PK-4509.09)*(Enemy_PK-4509.09)	-1.121e-8	2.954e-9	-3.80	0.0004
(MERS_PK-4509.09)*(MERS_PK-4509.09)	5.6675e-9	2.874e-9	1.97	0.0540
(MERS_PD-4509.09)*(MERS_PD-4509.09)	7.2386e-9	2.992e-9	2.42	0.0191

Table 2.   Table displays the estimate of the regression coefficient for each term, the associated standard errors, the t-Statistic, and significance of the terms.

The residuals of the fit should not display a pattern. The full model displays this in its residual plot (Figure 11).

Residual by Row Plot
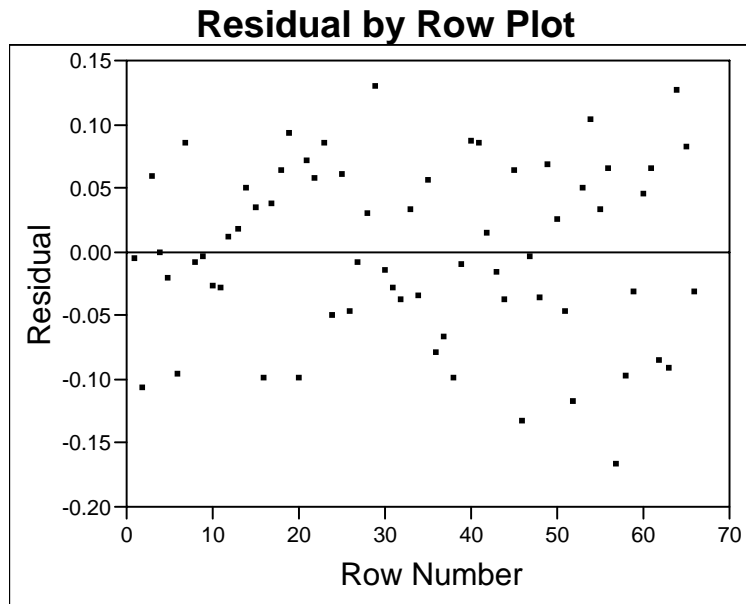
Figure 11.   Plot of the residuals from the full model.
              Note the lack of pattern (the desired result).

The interaction plots provide insights into how each
interaction will behave given defined values of the terms
in the interaction (Figure 12).
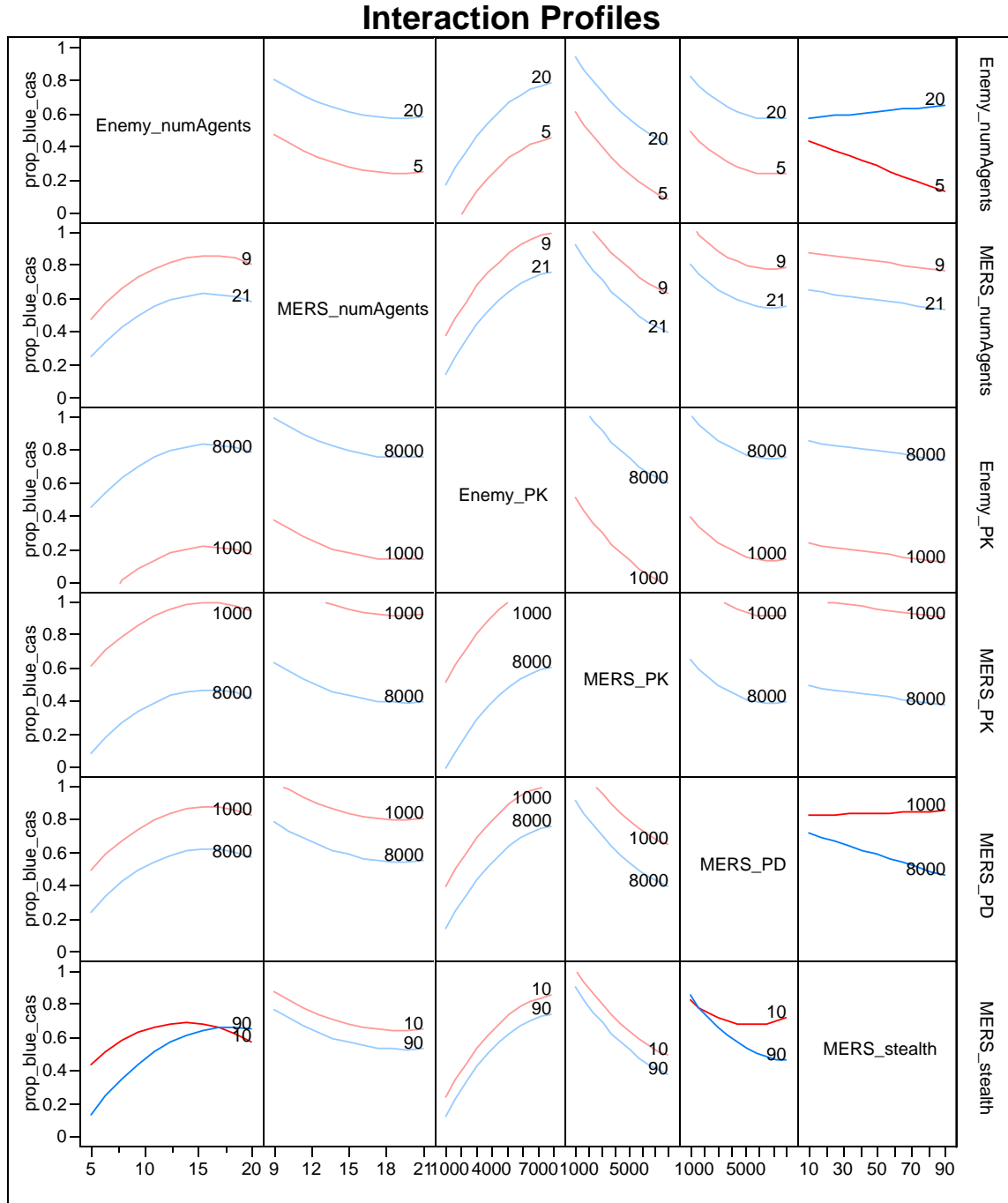
Figure 12. Interaction plots of the full model. Note: Only solid lines indicate an interaction.

In the analysis of creating the best model that describes the data, the author took number of parameters into account as well. Often models could be created that had minimal parameters and still exhibited adequate R Squared values. For example, in the creation of the model for the response of Proportion of Friendly Casualties, the complete model with 14 parameters (main effects and interactions) has an R Squared of 0.9485. Compare that result versus the 8 parameter model that has an R Squared of 0.9045 (Figure 13). A model that has fewer parameters may be more interpretable, and just as statistically sound, to decision makers.

PropFriendlyCasualties R Squared vs. # Parameters
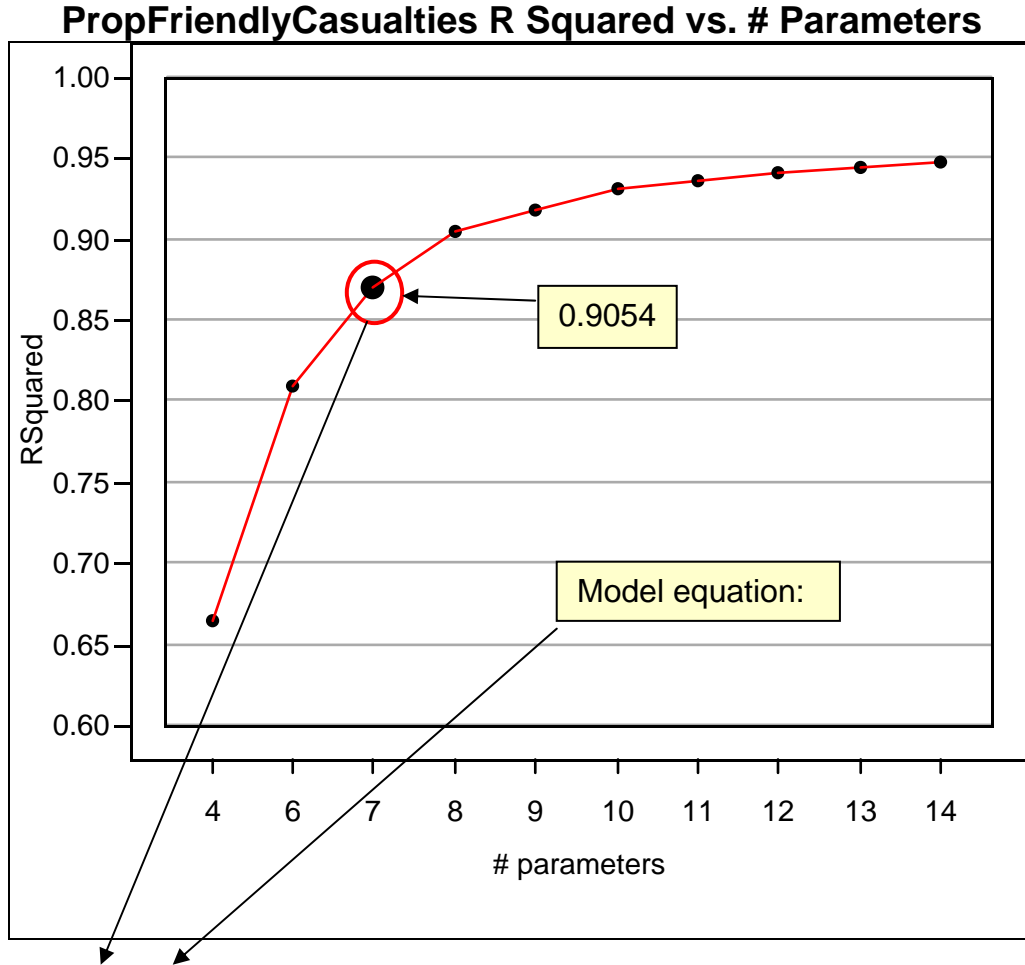
$$propFriendly Casualties = 0.836 + 0.018(Enemy\_numAgents)$$
$$-0.019(MERS\_numAgents) + 0.00008(survivability)$$
$$-0.00007(lethality) - 0.00004(sensor\_capability)$$
$$+0.0015(Enemy\_numAgents * MERS\_numAgents)$$
$$-0.0031(Enemy\_numAgents)^2$$

Figure 13.   Graph displays R Squared values vs. the number
             of parameters. The knee in the curve occurs at
             the 8 parameter mark (0.9054). The equation is
             the sample linear prediction for Proportion of
             Friendly Casualties.

The first term(s) that enter during the procedure are the interaction between survivability and lethality (with the main effects of each as well). These terms produce an R Squared of 0.6654. In further iterations of the algorithm, the interaction between survivability and lethality became insignificant and is removed.

Evaluating the LSE output of the preferred model, it is observed that the terms included in the model are all highly significant, with the exception of the interaction between the number of MERS agents and the number of enemy agents (Significance level just below the 10% threshold at 10.34%)(Table 3).

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.8361842	0.078373	10.67	<.0001
Enemy_numAgents	0.0183289	0.002663	6.88	<.0001
MERS_numAgents	-0.01924	0.003357	-5.73	<.0001
Survivability	0.0000877	0.000006	15.19	<.0001
Lethality	-0.000074	0.000006	-12.85	<.0001
Sensor Capability	-0.000035	0.000006	-6.11	<.0001
(Enemy_numAgents-12.5152)*(MERS_numAgents-15.0606)	0.0014966	0.000904	1.65	0.1034
(Enemy_numAgents-12.5152)*(Enemy_numAgents-12.5152)	-0.003052	0.000658	-4.64	<.0001

Table 3.   Table displays the estimate of the regression coefficient for each term, the associated standard errors, the t-Statistic, and significance of the terms.

Another important aspect is the scatter of the residuals from the generated fit. The residuals should display no defined pattern and they should be equally distributed above and below zero. The desired pattern is often compared to a shotgun pattern; randomly distributed in the plot. The residuals from the preferred fit generally display this desired characteristic (Figure 14).

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Residual by Predicted Plot
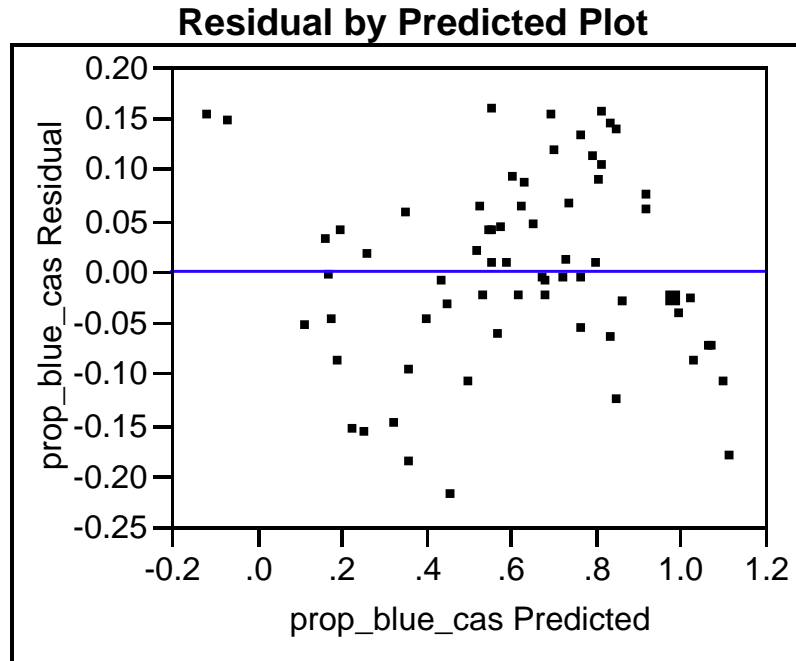
Figure 14.   Plot displays the desired pattern of the
             residuals from the preferred fit.   The
             residuals are randomly distributed about the
             plot.

      The preferred fit also contains two interesting terms;
MERS number of agents with Enemy number of agents and the
quadratic interaction of Enemy number of agents (Figure
15).   There is a diminishing return on Proportion of
Friendly Casualties for both high and low numbers of MERS
agents.   As   the   number   of   enemy   agents   increases,
Proportion of Friendly Casualties increases until the range
of 14 to 16 enemy agents.   Proportion of Friendly
Casualties also exhibits high sensitivity when the ratio of
the number of MERS agents to enemy agents is high.   For
large numbers of enemy agents, Proportion of Friendly
Casualties is more robust, averaging about 65% casualties.

Interaction Profiles
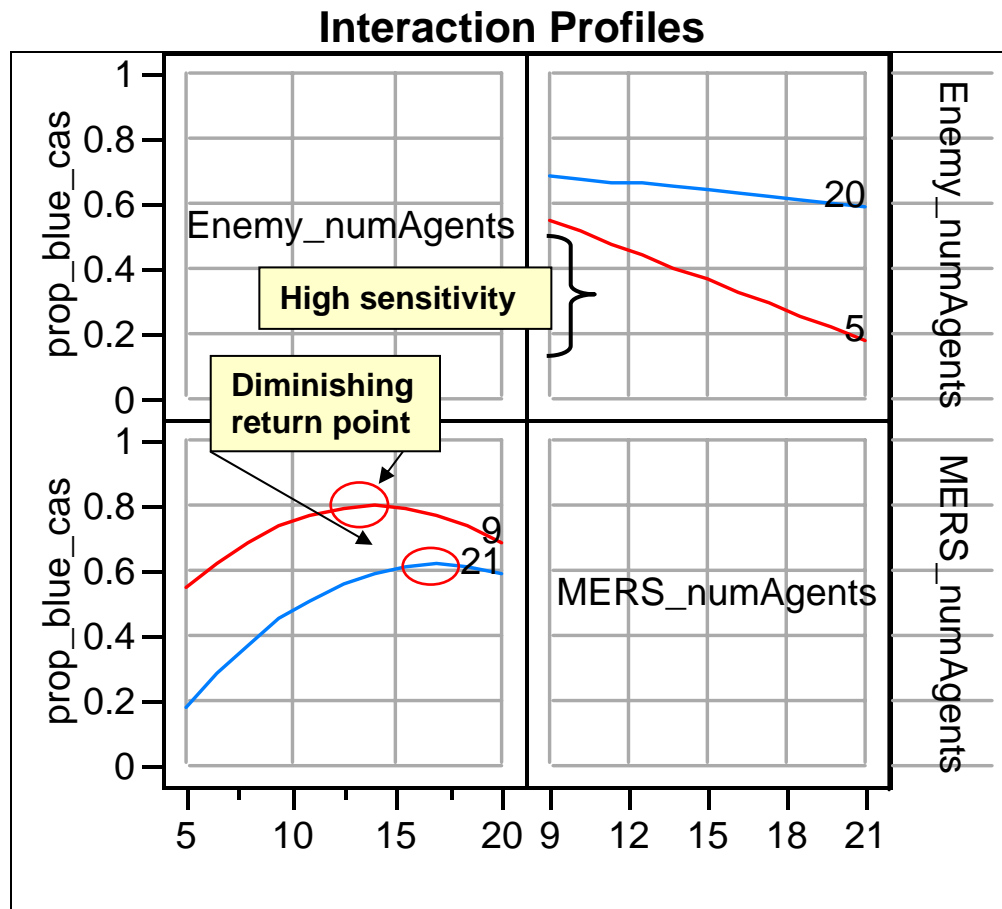
Figure 15.　Figure displays plot of interactions in the preferred fit.　Note; diminishing returns on the Proportion of Friendly Casualties are exhibited for both high and low levels of the number of MERS agents.　Also, the Proportion of Friendly Casualties is much more sensitive when the ratio of MERS agents to Enemy agents is high compared a lower ratio.

Hand-in-hand with the Stepwise and LSE Regressions is the Partition or Regression Tree.　The results from the partition coincide with the results from the other regressions (Figure 16).

All Rows

Count	66
Mean	0.6145959
Std Dev	0.3015656

Enemy_PK<1900

Count	8
Mean	0.1282815
Std Dev	0.0679976

Enemy_PK>=1900

Count	58
Mean	0.6816738
Std Dev	0.2556681

MERS_PK>=6300

Count	17
Mean	0.4520875
Std Dev	0.2516309

MERS_PK<6300

Count	41
Mean	0.7768681
Std Dev	0.1900772
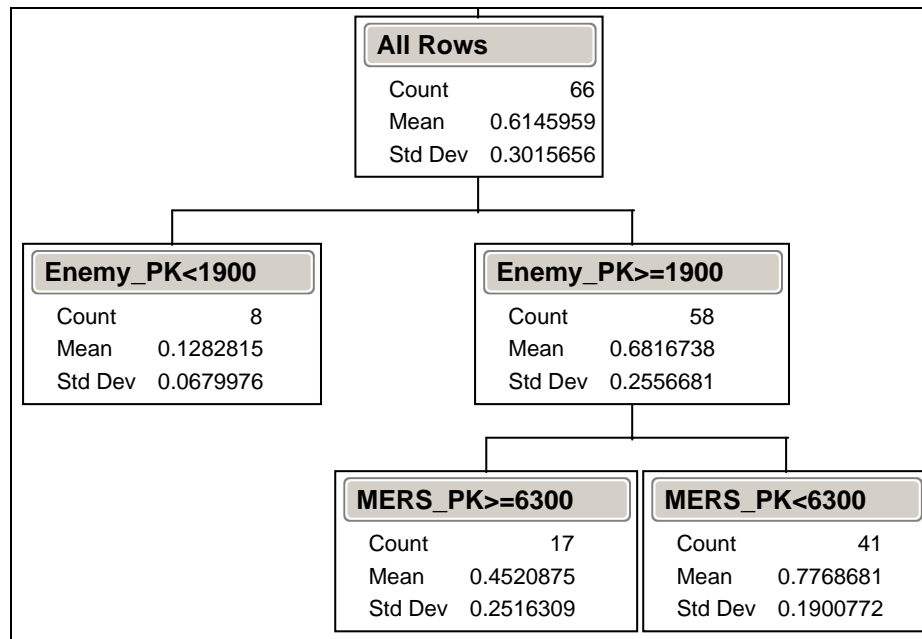
Parameter Contributions

Term	N Splits	SS	SS
Enemy_numAgents	0	0	
MERS_numAgents	0	0	
Enemy_PK	*1*	*2.15298097*	
MERS_PK	*1*	*1.26760749*	
MERS_PD	0	0	
MERS_SA_DLY	0	0	
MERS_stealth	0	0	
MERS_shot_taken_duration	0	0	
MERS_shot_at_duration	0	0	
MERS_sqd_shot_at_duration	0	0	

Figure 16.   Charts display partition results on MOE of Proportion of Friendly Casualties. Note that the first two levels of the partition graph that display the most significant factors are survivability (Enemy_PK) and lethality (MERS_PK). The table displays the significance of the parameters based on the calculation of the split statistic.

C.   STATISTICAL FINDINGS

The most significant finding is that *no main effects* show significance by themselves in the evaluation of LSE regression output for each MOE; the interactions (relationships between parameters in which changing a level of one has an effect on the other, resulting in an even

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greater effect on the measure) are critical in explaining the MOEs better (main effects are included as terms if they are part of an interaction). This highlights the need to evaluate the MERS as a system; simply evaluating the MERS by the modification of one parameter, one level at a time, will not allow for proper insights to be drawn. This necessitates the intense evaluation of interaction plots in order to help interpret the results.

Interactions are the most important factors to evaluate. This is understandable in small unit combat—which needs to be evaluated as a system; there is no magic wand that can be produced or procured that can sway the battle. The most important factors come in groups; one cannot have just a high PK, the need to be survivable as well creates the environment for success. This is analogous to the triad of fire; there must be air, spark, and fuel present for fire to occur.

D.   STATISTICAL INSIGHTS

   1.   Evaluation as a System

A single parameter (main effect) will not have the ability to provide comprehensive insights into the MERS. The relationships between parameters are the most important. This fact can be viewed in all evaluation of interactions. Neglecting this could lead to incorrect recommendations for equipping, employing, and supporting the MERS.

2. Survivability and Lethality

These two factors are the most important in the chosen scenario over the ranges examined (Figure 17). In analysis of partition regression, survivability and lethality are the largest split statistic for each MOE (see IV. Data Analysis, A. Overview for discussion on the split statistic). Survivability and lethality showing as the most significant parameters appeals to the intuitiveness of infantrymen; small units in close-in combat with no external support cannot succeed without them.
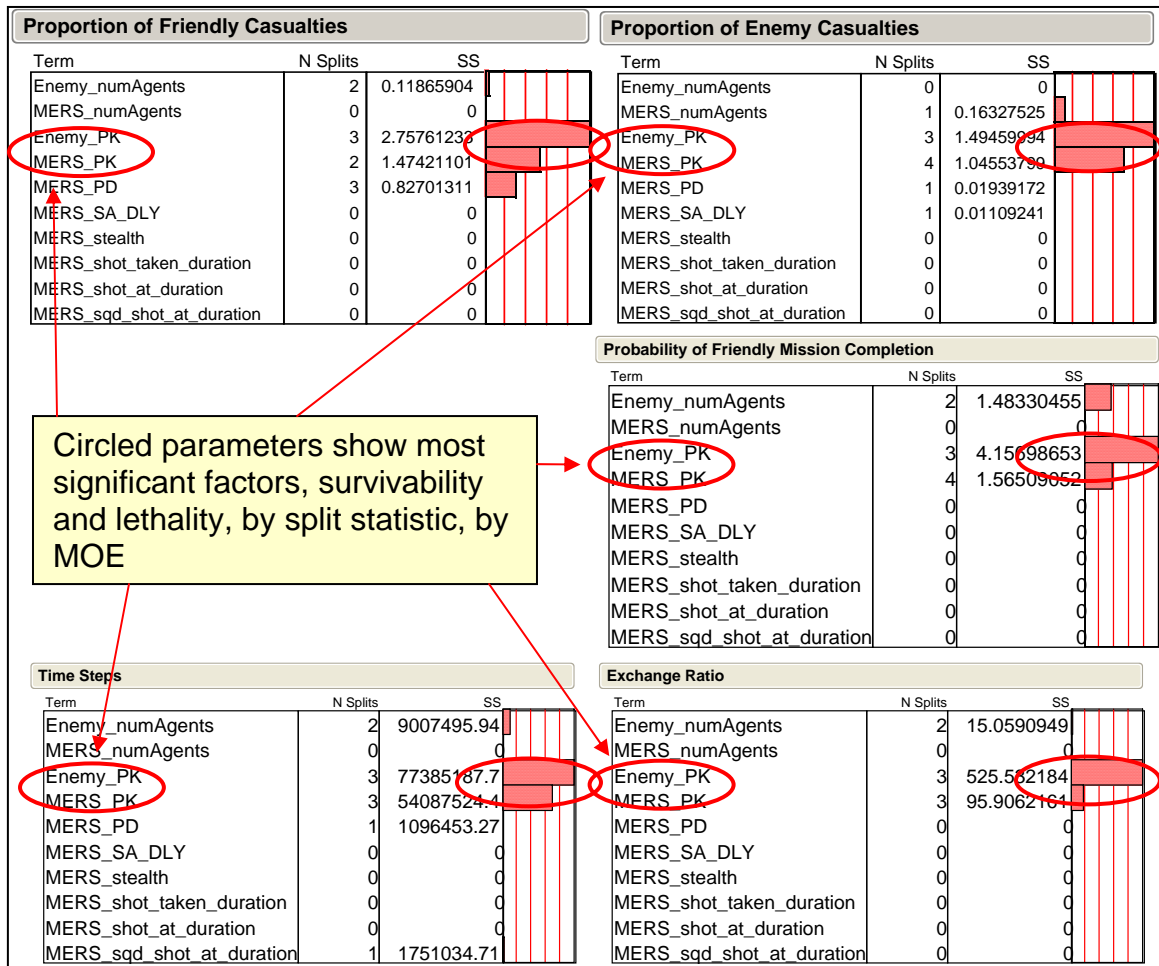
Figure 17.   Picture displays the significant parameters for each MOE by partition. Note: Lethality and survivability (MERS and Enemy PKs) contribute the most to each partition (circled parameters). Also, sensor capability (MERS_PD) and Situational Awareness (MERS_SA_DLY) showed next to no significance overall.

3. Mass is Still Significant

Mass, or the number of MERS agents and the number of Enemy agents, is significant, especially in their interaction with other parameters. The number of agents impact the proportion of casualties inflicted on one another (Figure 18). For large numbers of enemy (20), survivability has little effect on decreasing casualties. The biggest impact (reduction in casualties by 50%) occurs when the number of enemies is low and survivability is high.
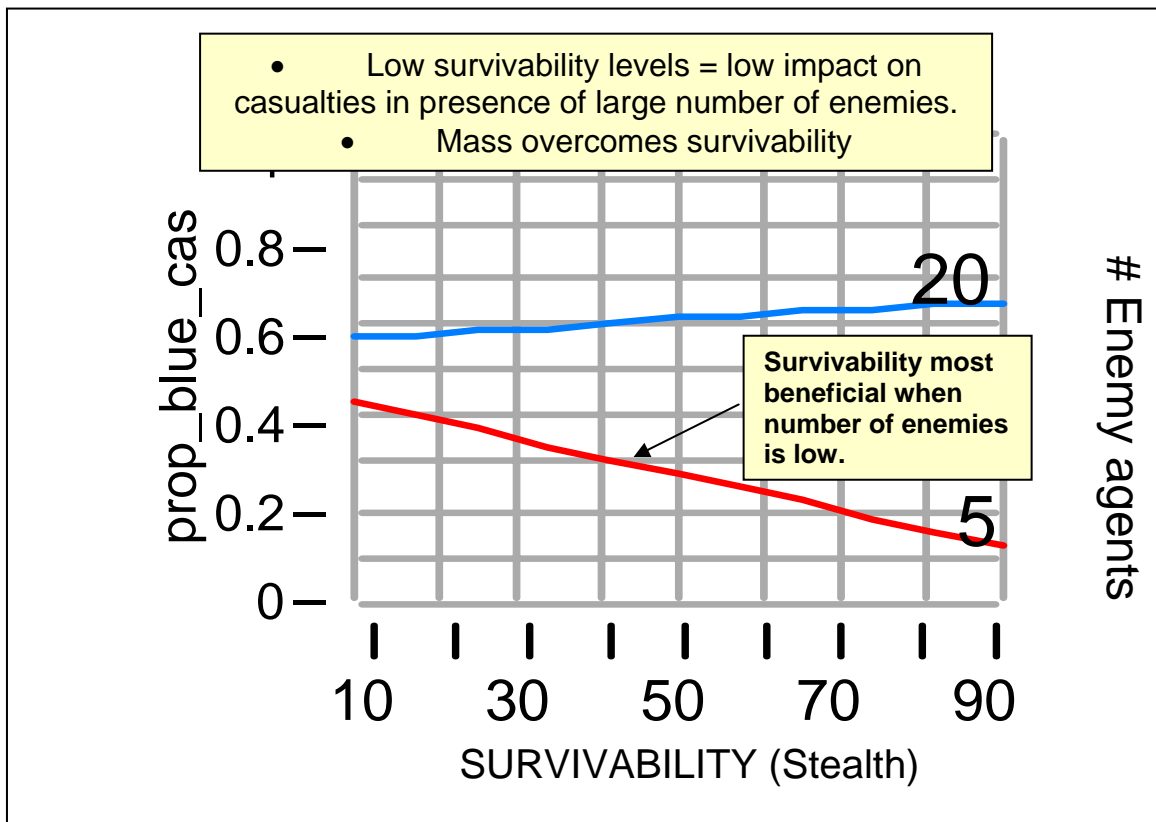
Figure 18.   Graph displays interaction between the number of enemy agents and survivability. Note: As the survivability of the MERS increased, the percent MERS killed drops by nearly one half, when the number of enemy was small. For large values of enemy, increasing the survivability of the MERS has little impact.

Survivability has the biggest impact when paired with the number of MERS agents (Figure 19). When survivability is low, the number of MERS agents has no effect in producing a good Exchange Ratio. As the number of MERS agents increases, the Exchange Ratio becomes better. For 13 MERS agents (standard infantry squad), the Exchange Ratio is about 1 to 7 in favor of the MERS. A unit that is not survivable will be less effective regardless of the size of the enemy force.
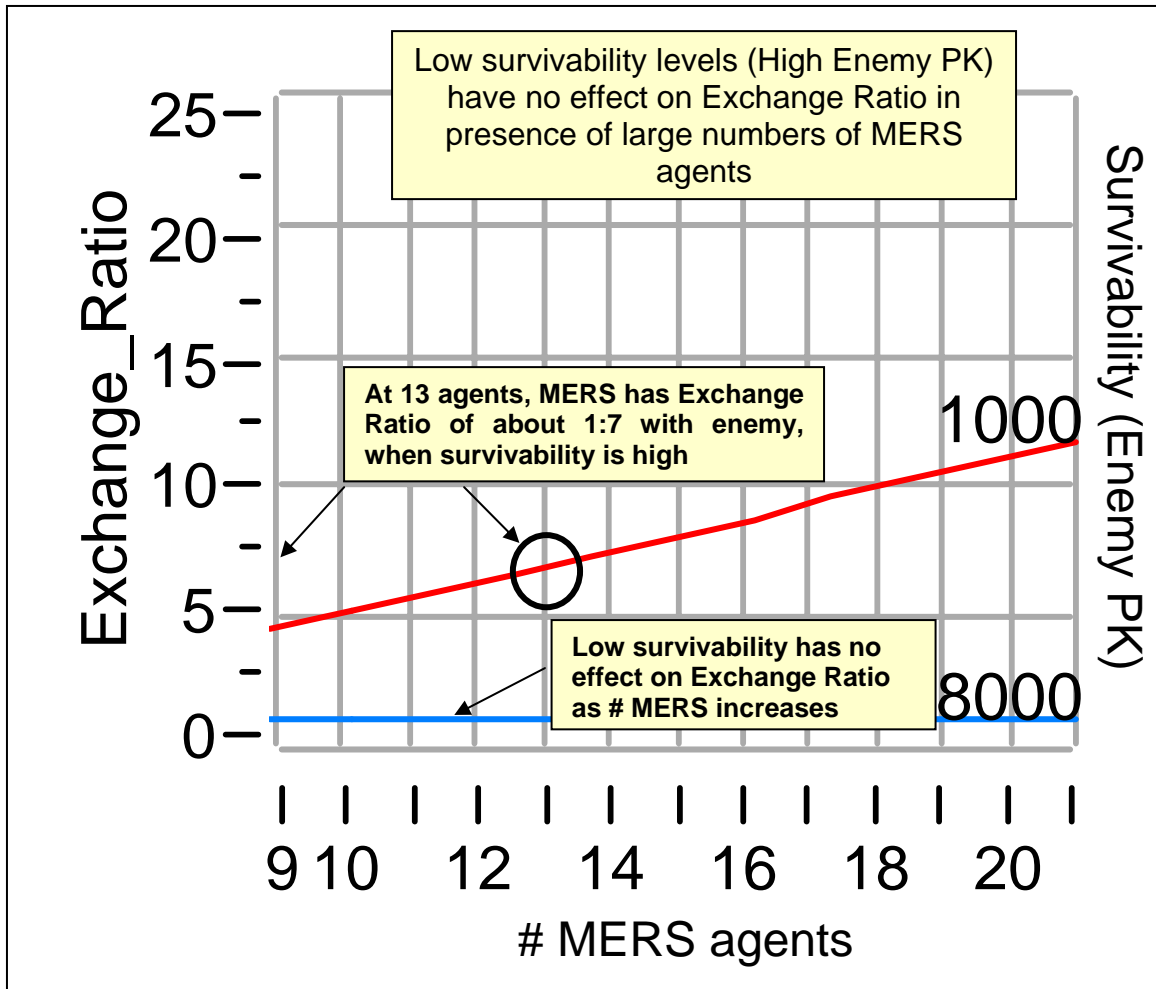
Figure 19.　　　Graph displays interaction between survivability and the number of MERS agents. Note: The Exchange Ratio is maximized when there are many MERS agents with high survivability. The number of agents has no impact on the Exchange Ratio when survivability is low. For a standard Marine squad (13), the Exchange Ratio is about 1:7.

The number of enemy forces has little effect on the accomplishment of the mission (Figure 20). Survivability is the most important factor; high survivability levels act as a force multiplier overcoming the mass of the enemy. Following the right branch of the partition, high survivability values (low Enemy PK) translate to an eight

fold increase in probability of mission completion. When the MERS lethality values are about two and a half times the enemy's values, the probability of mission completion is around 99% (bottom right branch of partition). The worst results are seen when low survivability is paired with low lethality in the left branch of the partition (a probability of mission completion of only 6%).

Partition of Probability of Friendly Mission Completion displaying importance of high survivability levels (Low Enemy PK)

All Rows
Count 66
Mean 0.2641414
Std Dev 0.3614458

When Survivability is high, by itself, probability of Mission Completion is 82%

Enemy_PK>=2100
Count 55
Mean 0.1521212
Std Dev 0.254083

Compared to 15%

Enemy_PK<2100
Count 11
Mean 0.8242424
Std Dev 0.2940487

MERS_PK<6500
Count 40
Mean 0.0608333
Std Dev 0.0924154

MERS_PK>=6500
Count 15
Mean 0.3955556
Std Dev 0.3713696

MERS_PK<4700
Count 6
Mean 0.6888889
Std Dev 0.3519259

MERS_PK>=4700
Count 5
Mean 0.9866667
Std Dev 0.0298142

Enemy_numAgents>=10
Count 9
Mean 0.1407407
Std Dev 0.1631102

Enemy_numAgents<10
Count 6
Mean 0.7777778
Std Dev 0.226732

99% Mission Completion when lethality and survivability are high!

Figure 20. Graph displays partition of Friendly Mission Completion. Note: High survivability will result in 8 times the probability of mission completion than low survivability. When coupled with high lethality (about a 2:1 ratio) results in almost 99% mission completion. The number of enemy agents comes third in significance.

4. Lack of Significance of Situational Awareness

In this scenario, Situational Awareness (SA) does not show significance by itself, but in some interactions proves very important (Figure 21, Figure 22). Increasing the number of MERS agents allows for an increase in mission completion when communication delays are both long (5 minutes) and short (zero), but both delays show diminishing returns. Computer models have the ability to process much more information than the individual combatant, but evaluating the delay of this processing (SA sharing) may highlight an example of information overload. This is present especially when the SA sharing delay is 5 minutes. There is some value to having networked, perfect information sharing structure that results in higher probability of mission completion. SA sharing shows less significance than other parameters because:

- Combat takes place at such short ranges

- There is so much ambiguity in the friend-or-foe evaluation, that by the time SA is shared, the agents already have first-hand knowledge of the situation.
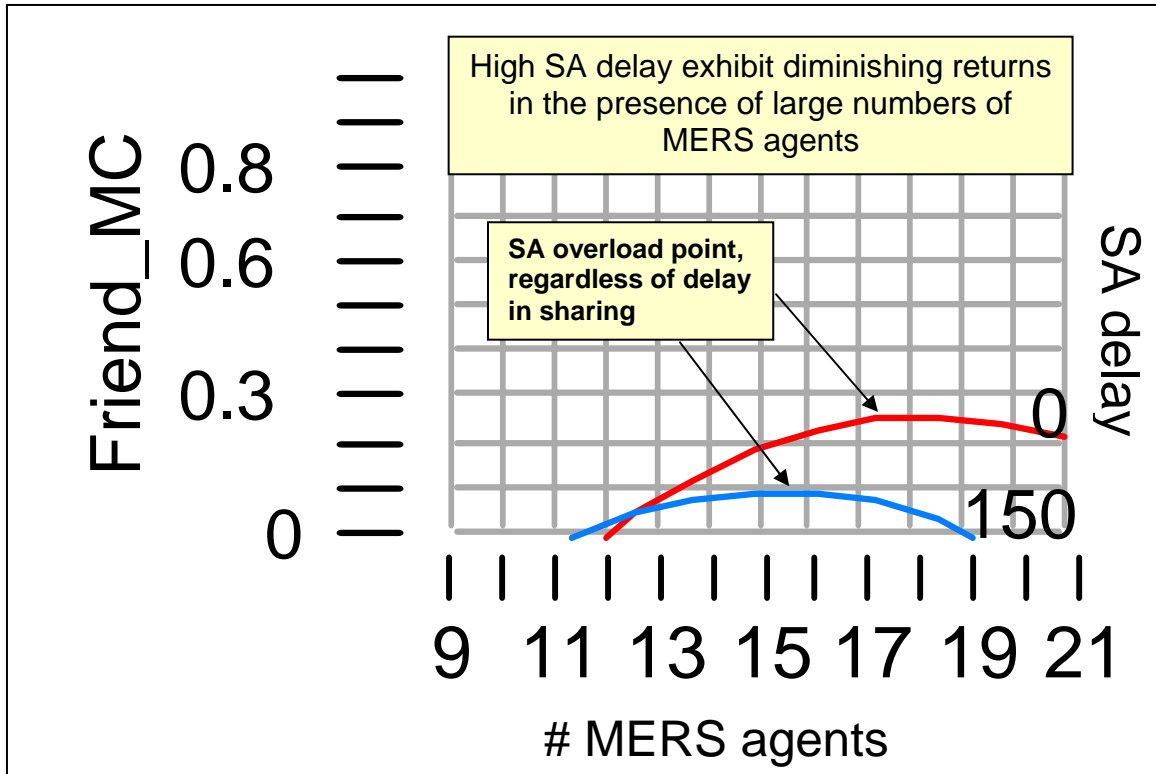
Figure 21.   Graph displays interaction between number of MERS agents and SA delay.   Note: For high values of delay (150 steps = 5 min), there is a diminishing return as the number of MERS agents increases.   There is a point of SA overload, where the probability of mission completion suffers regardless of delay length.   For low delay (0 steps), the number of agents increases mission completion success.   This is due to the fact that more agents equates to more eyes to identify the enemy.   Once a MERS agent identifies an enemy, the rest of the squad can orient and attack.
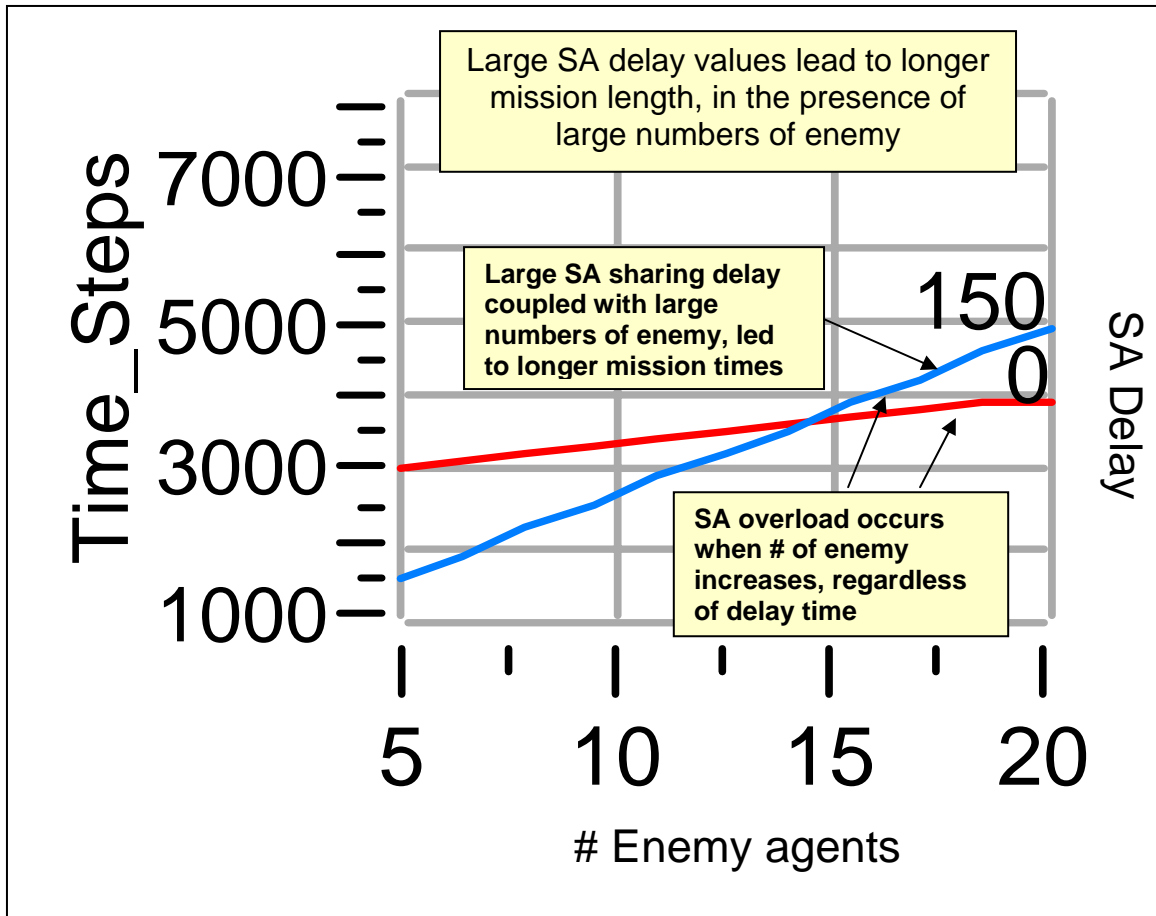
Figure 22.   Graph displays interaction between SA delay and number of Enemy agents. Note: For large values of delay (150 steps = 5 min), increased numbers of enemy led to increased length of mission. Low delay values lead to a minor effect when enemy agents increased.

IV. RECOMMENDATIONS AND ADDITIONAL INSIGHTS

A.   RECOMMENDATIONS

1.   MERS Effectiveness and Employment

- **Evaluation of the MERS must be done as a system.** The interactions between parameters require a system approach be applied.

- **Employing weapons and equipment that provide the most lethal and survivable unit will ensure the most effective MERS.** Lethality should be viewed as the MERS ability to project combat power; e.g., weaponry. Survivability should be viewed as anything that can defeat the enemy's projection of combat power; e.g., body armor, camouflage, or in today's networked world, even electronic countermeasures. It is important to note that increasing lethality and survivability cannot be accomplished piecemeal (evident from the strong interactions).

- **The tradeoff between mass and SA sharing must be closely examined.** The MERS should be employed as large a force as possible that does not interfere with the mission. Mass allows the MERS to defeat enemy formations. Effective SA sharing in the presence of a larger unit can be problematic. There was a diminishing return of mission completion as the unit grew, most likely due to SA overload. It is the author's experience that the more members of a unit focus on information being relayed to them, vice focusing on the situation themselves, results in a less effective unit.

2. Agent-based Modeling as an Analysis Tool

The future application of agent-based modeling as an analysis tool is unlimited. As the modeling needs of the Department of Defense (DoD) become greater, one can count on the quality of agent models to improve. Likewise, the culture of modelers in DoD will begin to be more receptive to the use of agent-based models. This sets the stage for first class analysis that utilizes all of the tools available.

An important principle for the use of agent-based models is the fact that this set of models is intended to compliment the suite of physics-based models. The Army has shown that use of agent- and physics-based models in concert will benefit the modeling process in whole (Cioppa, 2002). To that end, the author believes it is important

for DoD to integrate agent-based models into its analysis. The addition of agent-based models will add to the robustness of current research efforts.

3.   Further Research and Analysis

All employment and structure recommendations are, of course, limited to the context of this scenario. That being said, the seeds are planted for further research to be conducted. The surface of research and analysis has only been scratched in this scenario. The research and analysis has explored a specific scenario with a specific environment. In order to add to the robustness of the analysis, it is vital to explore differing terrains and mission profiles.

The addition of different mission profiles and support packages is important as well. An IDF scenario has been examined only basically and needs more in depth analysis. The author suggests the exploration of support of some inorganic sensor unit (UAV, reconnaissance team, sniper, etc.).

Based on some Marine Corps Warfighting Laboratory experiments utilizing a squad designated marksman (DM) (Marine Corps Warfighting Laboratory, 2000), an evaluation of the effect of an added DM in the MERS could be beneficial. A trade-off analysis of equipping and training the entire MERS to perform the DM mission versus the addition of a varied number of DM's is suggested as well.

Scaling of the scenario into next level units will add insight into the addition of external asset needs versus small unit capabilities. The addition of some eye-in-the-sky or an on station air-to-ground asset may mitigate the need for the individual to have a high PK.

B.   ADDITIONAL INSIGHTS

1.   Force

Overall, the number of Marines that would be a part of the MERS makes little statistical impact. When the parameter is influential (such as in producing a higher proportion of enemy casualties), the trend is to recommend larger numbers of Marines. This follows the reasoning of the concept of mass; the number of rifles in the fight can still make the difference.

On the enemy side, similar trends are observed. Larger enemy units are able to affect the fight more often (such as in producing a higher proportion of friendly casualties, increasing the length of a mission, and decreasing the probability of mission completion). It would be interesting to be able to evaluate a metric based on the size of enemy involved in each contact. The author observed many times that a larger, concentrated enemy force produced more casualties. This may be observed through further modeling of a scripted enemy force that is stationary and changes in size or, by adjusting the enemy behaviors to be more inclined to mass. As for the friendly forces, mass shows to be important.

2. Tactical

Fire and maneuver is still king in small unit combat. The basic principles of fixing the enemy with fires, and then moving to engage their weakness hold true (see FMFM 6-5 Marine Rifle Squad, page 2-31). This successful technique was usually observed through hundreds of replications of the scenario.

The use of indirect fires in order to gain superiority over the enemy is vital in the indirect fire (IDF) scenario. A well supported small unit has the ability to overcome a much larger force. This allows for economy of force, freeing other units to accomplish additional missions.

3. Terrain

In evaluation of the scenarios modeled, it is obvious that the terrain is an important factor. Urban terrain is an environment that is ruthless, even to computer combatants. The lack of LOS, adequate maneuverability, and the occurrence of close-in combat can overwhelm the unit. This is an area which translated well in real-world-to-model. The urban battlefield negated complex and advanced communication capabilities and sensor effects, limited maneuver, and reduced stand-off from the enemy, resulting in a more deadly environment.

Given the LOS based sensors, it would be desirable to develop a sensor that provided better capabilities in an urban environment. Firefights are most often reactive due to the limited detection ability of the MERS. The combat is characterized by the MERS essentially stumbling into an

enemy force and then utilizing fire and maneuver to destroy them.   Further modeling should be explored in which the 100% concealment values of the buildings could be varied in order to evaluate some sensor that can overcome walls.

4.   Emergent Behavior

One of the most interesting effects of using an agent-based model is the experience of emergent behavior ("the process of complex pattern formation from simpler rules" (Wikipedia, 2005)).   This occurs when the agents modeled make decisions based on behavioral rules vice scripting. The more accurately the behaviors are developed, the more accurate the emergent behavior becomes.

The primary scenario modeled, along with the Indirect Fire (IDF) scenario excursion, both exhibited emergent behavior.   In the base scenario, the MERS exhibited emergent behavior during firefights with the insurgent forces.   Most often, the firefight began with the front of the MERS column being engaged by an insurgent force.   This led to several state changes of the agents in the squad. Through these state changes and associated behaviors, the agents in the rear of the MERS column would essentially find cover, and then begin to maneuver on the insurgent force (commonly resulting in traditional flanking or double envelopments), based on their defined behaviors.   There was no scripting for the agents to follow; the agents used their defined behaviors, resulting in the flank maneuver.

In the IDF scenario, the MERS exhibited the same small unit firefight behavior.   An interesting example of emergent behavior occurred when the MERS was able to utilize IDF to engage the enemy.   IDF was available to the

MERS during the entire scenario (except during 'out-of-action' time between shots), yet the MERS seemed only to utilize the IDF when faced with an enemy they could not quickly dispatch. For example, as the MERS came into contact with a small (say < 4) enemy, they would usually easily destroy the enemy force without IDF. As the enemy force began to compare in size to the MERS, more protracted firefights would occur. These longer firefights would result in the MERS utilizing their IDF to gain an advantage on the enemy due to the delay in accomplishing the mission. There was no interaction of the modeler to base IDF usage on force ratio, enemy size, or time of firefight. The MERS agents evaluated the situation and, based on the predefined behaviors, utilized IDF.

Of course, even these simple examples may seem farfetched. Currently, it is impossible to capture this emergent behavior via some metric. MANA enables the modeler to view a well developed animated run of the scenario. The author asserts the existence of emergent behavior based on the thousands of runs he has viewed. The development of a metric would aid in the validation of emergent behavior, enabling a better understanding of this cutting edge capability.

C.   CONCLUSION

Small unit combat necessitates the evaluation of interactions in order to gain insights into improving unit effectiveness. This highlights the need for evaluation of the MERS as a system.

The individual combatant is both the most fragile and most sturdy of units in warfare. They have the ability to neutralize forces that are larger, stronger, and more lethal. They can also be destroyed by the simplest of means. This fact serves to highlight the need for increased lethality and survivability. As the transformation of the American Armed Forces heads forward, the rift between those who believe in investment in individuals and those who believe in investment in material grows larger.

One thing will always be true; at the end of the day, it is the individual Marine, Soldier, Sailor, and Airman that affect the fight more than any system. Investment in improving the method that these individuals complete the mission is always advisable. This research has shown that focusing efforts in some key areas, lethality and survivability, while evaluating the relationship between them, can lead to overall mission success; kill the enemy, protect our force, and accomplish the mission.

APPENDIX A. PARTITION GRAPHS

The partition graphs display the series of splits executed, based on the size of the split statistic (see IV. Data Analysis, A. Overview for discussion on the split statistic). In order to interpret the graph, begin at the top center (the root) and follow the subsequent splits to identify the most significant parameters. The numerical values displayed are the level at which the previous parameter was split. In this set up, the most significant parameters begin with the root, and follow down the graph in order of significance. The values displayed are relative levels that the partition found the split statistic to be the largest, indicating the need for a new branch.

A. PROBABILITY OF FRIENDLY MISSION COMPLETION
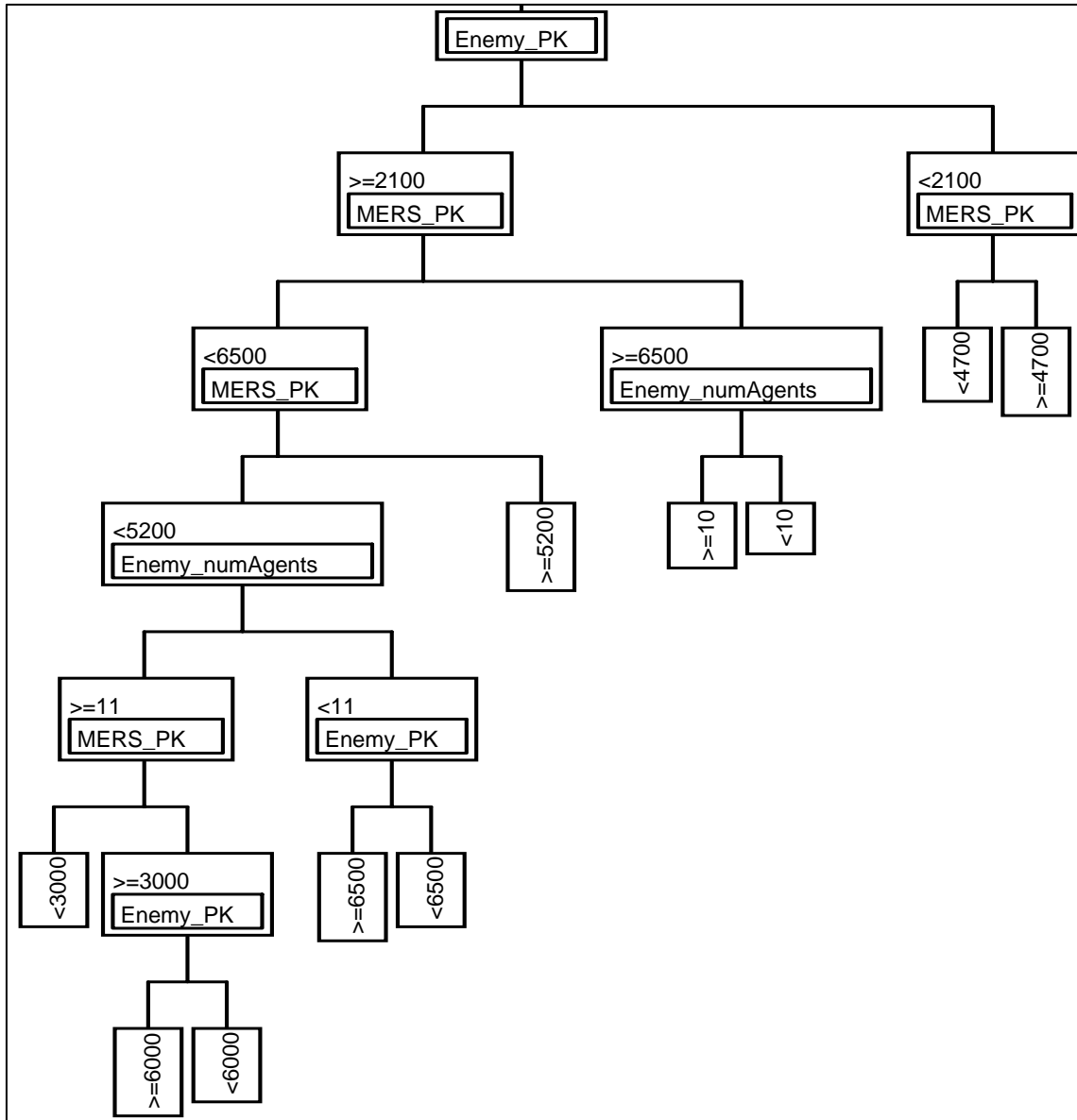
```
                              ┌──────────┐
                              │ Enemy_PK │
                              └──────────┘
                    ┌─────────────────────────────────┐
            ┌─────────────────┐              ┌─────────────────┐
            │ >=2100          │              │ <2100           │
            │ MERS_PK         │              │ MERS_PK         │
            └─────────────────┘              └─────────────────┘
           ┌───────────────────────┐          ┌──────┐
   ┌─────────────────┐   ┌─────────────────┐  │<4700 │  │>=4700│
   │ <6500           │   │ >=6500          │
   │ MERS_PK         │   │ Enemy_numAgents │
   └─────────────────┘   └─────────────────┘
      ┌────────────────┐     ┌──────┐
┌─────────────────┐  ┌──────┐ │>=10 │ │<10│
│ <5200           │  │>=5200│
│ Enemy_numAgents │
└─────────────────┘
   ┌───────────────────┐
┌─────────────────┐  ┌─────────────┐
│ >=11            │  │ <11         │
│ MERS_PK         │  │ Enemy_PK    │
└─────────────────┘  └─────────────┘
   ┌──────────────┐     ┌──────┐
┌──────┐ ┌─────────────┐ │>=6500│ │<6500│
│<3000 │ │ >=3000      │
│        │ │ Enemy_PK    │
         └─────────────┘
            ┌──────────┐
         ┌──────┐ ┌──────┐
         │>=6000│ │<6000 │
```

The root displays the most significant factor as survivability. The next level displays lethality as the second most significant factor. Note: Situational Awareness is not a significant factor at all.

B. PROPORTION OF FRIENDLY CASUALTIES
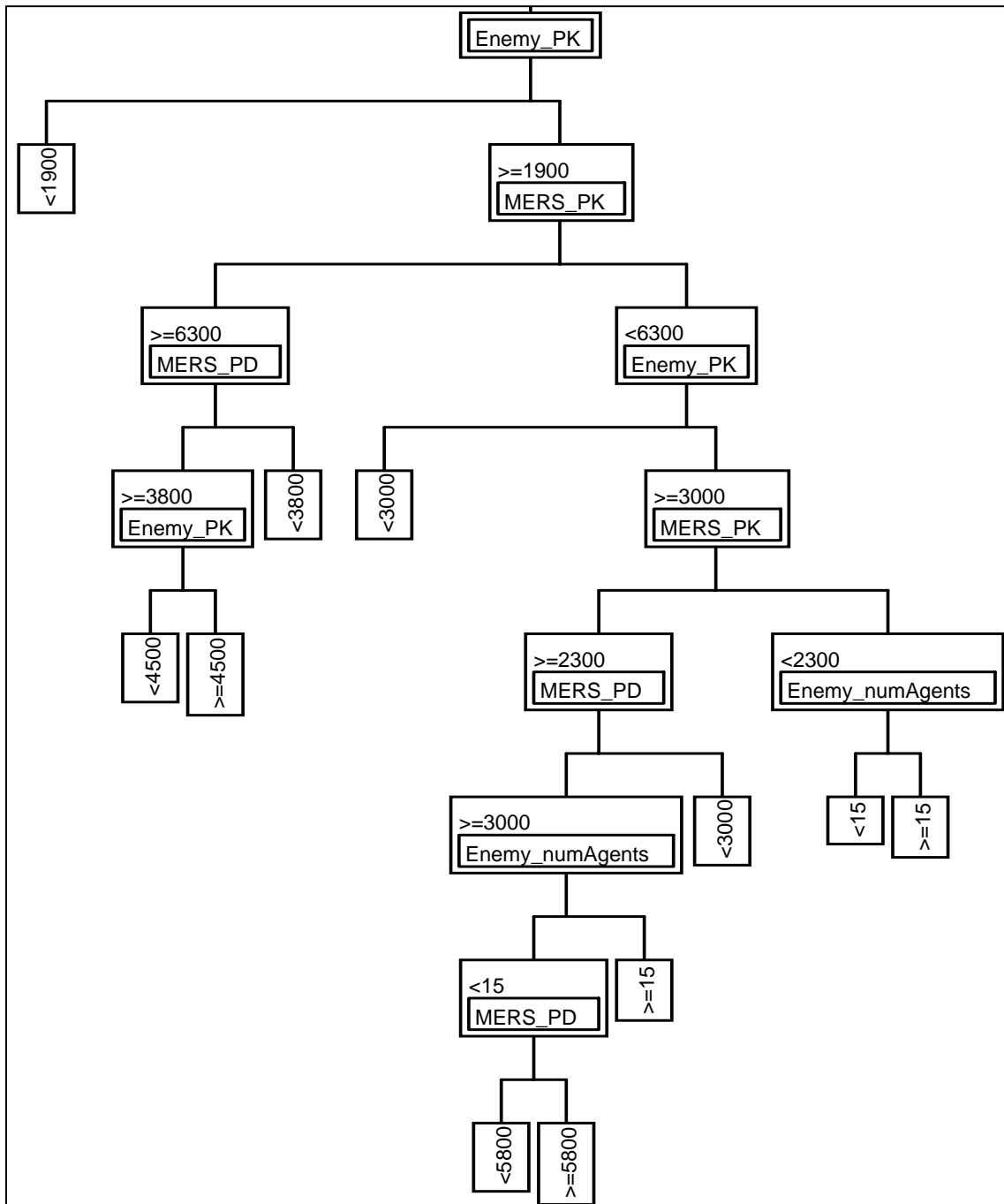
```
                              Enemy_PK
                                 |
          ┌──────────────────────┴──────────────────────┐
        <1900                                         >=1900
                                                     MERS_PK
                                                        |
                                 ┌──────────────────────┴──────────────────────┐
                              >=6300                                          <6300
                              MERS_PD                                        Enemy_PK
                                 |                                              |
                    ┌────────────┴────────────┐                 ┌──────────────┴──────────────┐
                 >=3800                      <3800            <3000                          >=3000
                 Enemy_PK                                                                   MERS_PK
                    |                                                                          |
            ┌───────┴───────┐                                              ┌───────────────────┴───────────────────┐
          <4500          >=4500                                         >=2300                                    <2300
                                                                        MERS_PD                              Enemy_numAgents
                                                                           |                                       |
                                                              ┌────────────┴────────────┐              ┌───────────┴───────────┐
                                                           >=3000                      <3000          <15                     >=15
                                                        Enemy_numAgents
                                                              |
                                                  ┌───────────┴───────────┐
                                                 <15                     >=15
                                                 MERS_PD
                                                    |
                                          ┌─────────┴─────────┐
                                        <5800             >=5800
```

The root displays the most significant factor as survivability. The next level displays lethality as the second most significant factor. Note: Situational Awareness is not a significant factor at all. Enemy mass is slightly significant.

C. PROPORTION OF ENEMY CASUALTIES
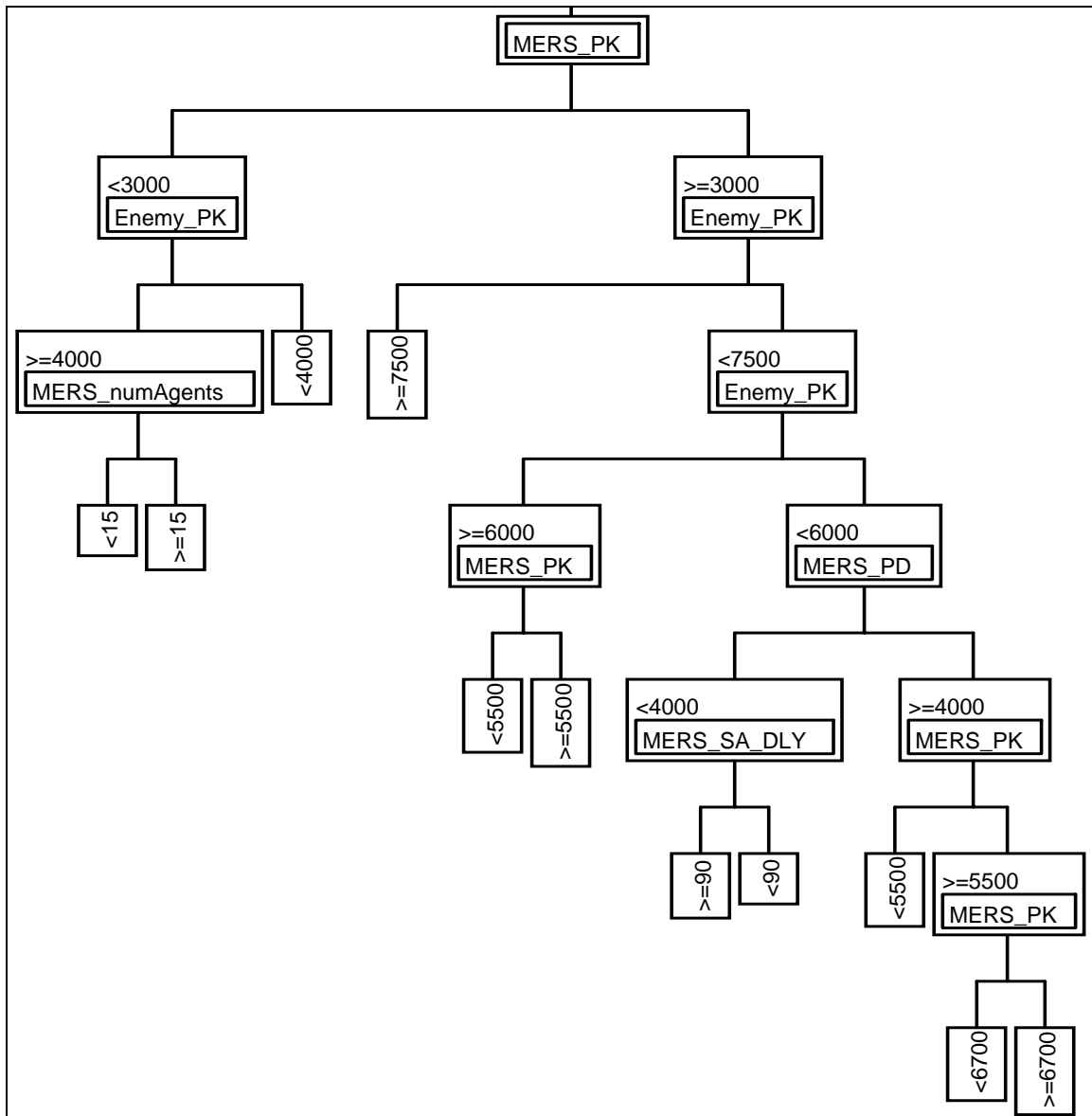
The root displays the most significant factor as survivability. The next level displays lethality as the second most significant factor. Note: Situational Awareness shows low significance. MERS mass shows low significance.

D.   EXCHANGE RATIO

```
                            Enemy_PK

              >=1900                          <1900
              MERS_PK

         <7500                        >=7500
         Enemy_numAgents

    >=8                      <8
    MERS_PK

 <3000                   >=3000
 Enemy_numAgents         Enemy_PK

      >=15   <15     >=6300            <6300
                     Enemy_PK         MERS_PK

                 >=7500  <7500    <5500  >=5500
```

The root displays the most significant factor as survivability.   The next level displays lethality as the second most significant factor.   Note: Situational Awareness is not a significant factor at all.   Enemy mass shows some significance.

E.   TIME TO MISSION COMPLETION

The root displays the most significant factor as lethality. The next level displays survivability as the second most significant factor. Note: Situational Awareness is not a significant factor at all. Enemy mass shows some significance.

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APPENDIX B. DESIGNS OF EXPERIMENT

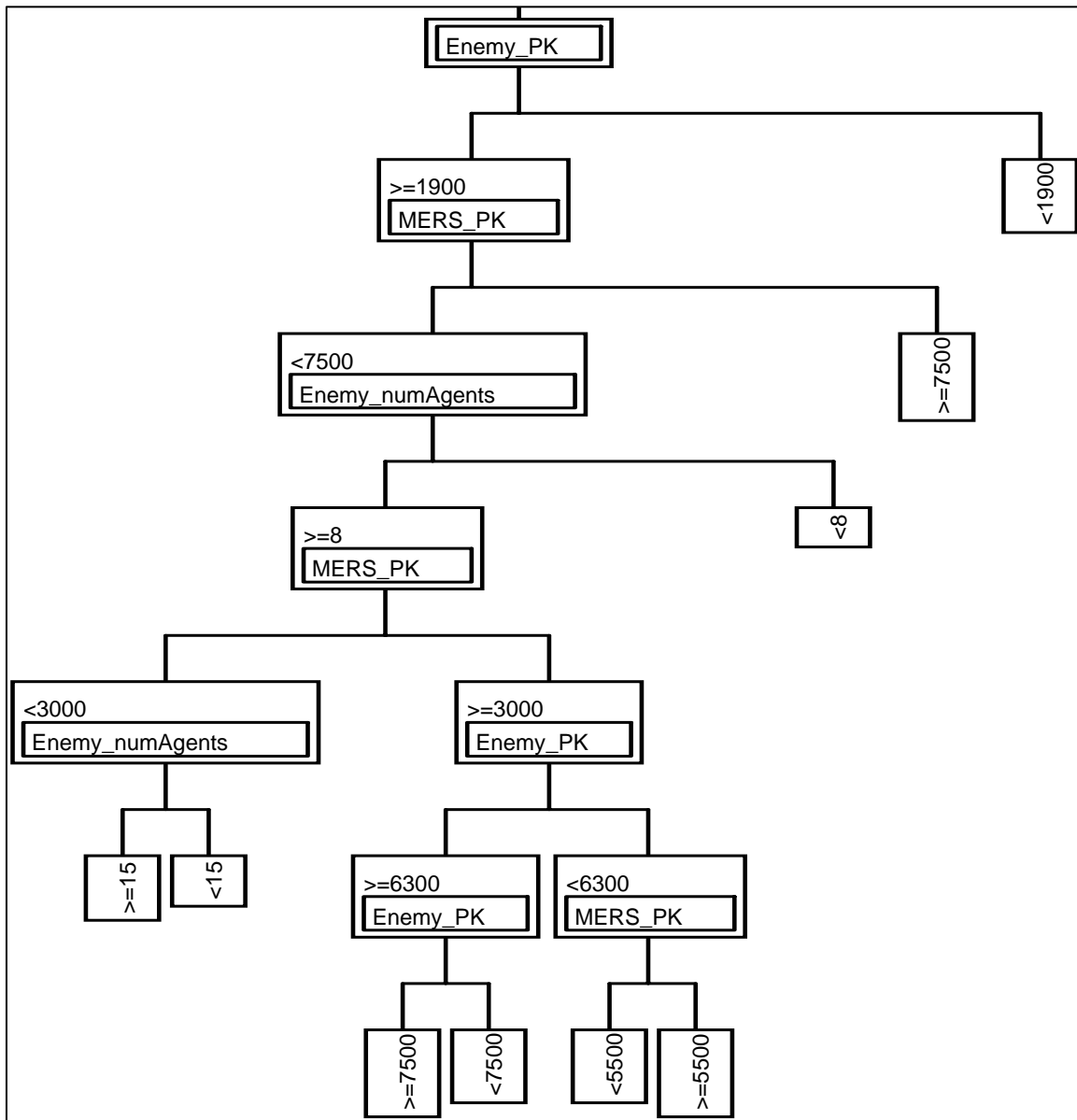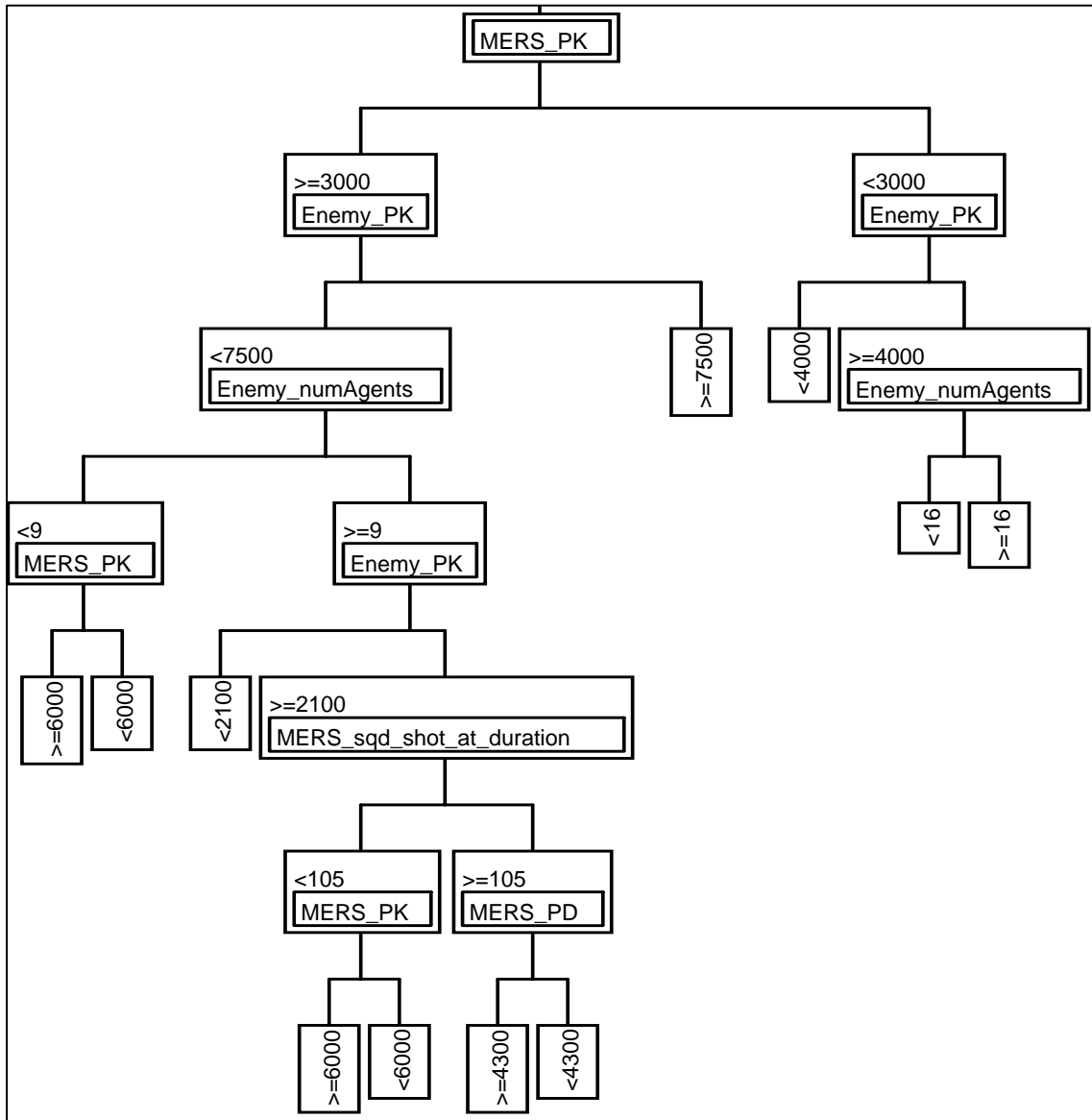| Excursion	Enemy_ numAgents	MERS_ numAgents	Enemy_PK	MERS_PK	MERS_PD	MERS_ SA_DLY	MERS_ stealth	MERS_shot_ taken_duration	MERS_shot_ at_duration	MERS_sqd_shot_ at_duration
1	20	14	1700	7100	5400	30	90	15	150	105
2	19	11	8000	4300	2300	60	80	10	135	75
3	18	20	4100	1200	5200	30	80	2	60	150
4	13	21	7100	7600	2100	60	60	3	75	30
5	19	15	1200	5800	6000	30	90	17	30	30
6	20	13	7600	4100	2500	45	90	26	15	90
7	15	21	4300	1000	5600	45	70	27	135	15
8	13	20	5800	7300	2800	45	50	30	90	135
9	15	12	2800	6000	3200	75	60	6	90	90
10	16	12	5600	2500	4700	105	70	12	135	45
11	16	18	2500	3400	1400	150	70	6	60	105
12	17	17	6000	6300	7800	135	70	13	45	30
13	14	11	2100	5200	1900	90	60	24	60	60
14	18	14	5200	2100	4900	135	80	22	45	120
15	14	19	2300	3600	1000	135	60	23	105	60
16	17	16	5400	6700	7300	150	80	20	120	120
17	13	15	4500	4500	4500	75	50	16	90	90
18	5	16	7300	1900	3600	120	10	16	15	60
19	6	20	1000	4700	6700	90	20	21	30	90
20	7	10	4900	7800	3800	120	20	29	105	15
21	12	9	1900	1400	6900	90	50	28	90	135
22	6	15	7800	3200	3000	120	20	14	135	135
23	5	17	1400	4900	6500	105	10	5	150	75
24	10	9	4700	8000	3400	120	40	4	30	150
25	12	10	3200	1700	6300	105	50	1	75	30
26	10	18	6300	3000	5800	75	40	25	75	75
27	9	18	3400	6500	4300	45	30	19	30	120
28	9	12	6500	5600	7600	0	30	25	105	60
29	8	13	3000	2800	1200	15	30	18	120	135
30	11	19	6900	3800	7100	60	40	7	105	105
31	7	17	3800	6900	4100	15	20	9	120	45
32	11	11	6700	5400	8000	15	40	8	60	105
33	8	14	3600	2300	1700	0	30	45	45	30

Excursion	Enemy_ numAgents	MERS_ numAgents	Enemy_PK	MERS_PK	MERS_PD	MERS_ SA_DLY	MERS_ stealth	MERS_shot_ taken_duration	MERS_shot_ at_duration	MERS_sqd_shot_ at_duration
34	14	17	4500	8000	6000	150	20	20	45	135
35	8	18	3000	7500	4000	140	90	7	60	75
36	14	18	1000	3000	8000	130	50	41	30	15
37	7	19	1500	4000	1500	80	80	45	75	135
38	16	14	5000	1500	2000	140	10	22	45	105
39	8	11	7000	1000	4500	150	90	15	60	75
40	15	14	7500	7000	1000	100	50	44	45	15
41	9	12	8000	4500	7500	80	70	42	60	135
42	10	9	2500	5000	5000	100	30	11	90	105
43	13	10	3500	7000	2500	110	60	13	105	45
44	6	11	2000	3500	5500	110	30	34	150	60
45	20	15	4000	2500	2000	120	70	30	135	120
46	7	21	6500	3500	3000	90	20	9	90	90
47	13	20	6000	3000	6500	130	60	18	135	30
48	5	17	6500	6000	3500	90	30	38	135	60
49	19	16	5500	6500	6500	120	60	27	150	120
50	13	15	4500	4500	4500	80	50	23	90	90
51	11	13	4500	1000	3000	0	80	26	120	30
52	17	12	6000	1500	5000	10	10	40	105	90
53	11	12	8000	6000	1000	20	60	5	135	150
54	18	11	7500	5000	7500	70	20	1	90	30
55	9	16	4000	7500	7000	10	90	24	120	60
56	17	19	2000	8000	4500	0	20	31	105	90
57	10	17	1500	2000	8000	50	50	2	120	150
58	16	18	1000	4500	1500	70	40	4	105	30
59	15	21	6500	4000	4000	50	70	35	75	60
60	12	20	5500	2000	6500	40	40	33	60	120
61	19	20	7000	5500	3500	40	70	12	15	105
62	5	15	5000	6500	7000	30	30	16	30	45
63	18	9	2500	5500	6000	60	80	37	75	75
64	12	10	3000	6500	2500	20	40	29	30	135
65	20	13	3000	3000	5500	60	80	8	30	105
66	6	14	3500	2500	3000	30	40	19	15	45

Table 4.   Tables display the DOE evaluated. Note: PKs and PD are coded for MANA; e.g., dividing the value by 10,000 produces a traditional PK between 0 and 1 (5000 / 10000 = 0.5). SA Delay and the other duration parameters are coded as well. The value listed is time steps. One time step equals two seconds. All other values are un-coded.

APPENDIX C. LINEAR REGRESSION EXAMPLE

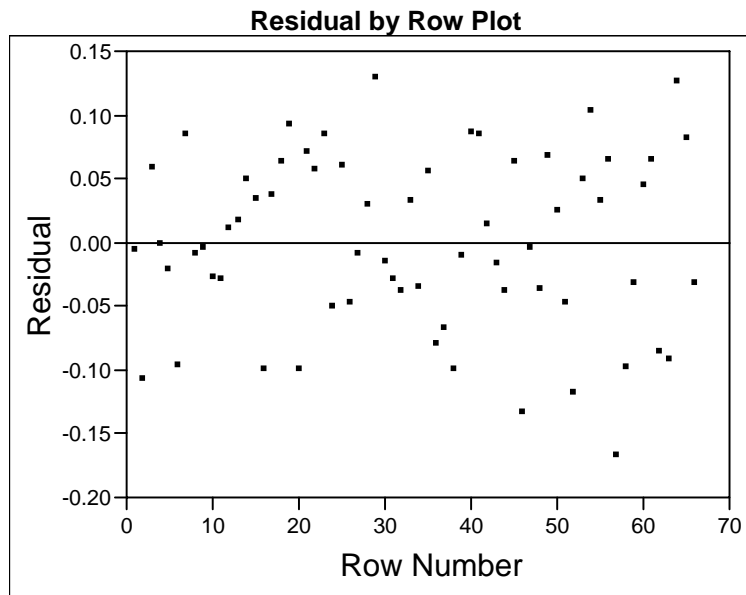## A. FULL MODEL REGRESSION: PROPORTION OF FRIENDLY CASUALTIES
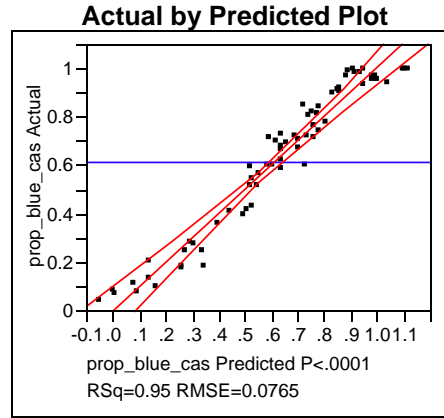
Actual by Predicted Plot

RSq=0.95 RMSE=0.0765

Summary of Fit

RSquare	0.948545
RSquare Adj	0.935681
Root Mean Square Error	0.076481
Mean of Response	0.614596
Observations (or Sum Wgts)	66

The amount of explained variation in the model is 0.9485 with a model variance of 0.076 (a very good fit).

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.812676	0.069167	11.75	<.0001
Enemy_numAgents	0.0221447	0.002397	9.24	<.0001
MERS_numAgents	-0.019179	0.002617	-7.33	<.0001
Enemy_PK	0.0000881	0.000005	19.55	<.0001
MERS_PK	-0.000075	0.000004	-16.66	<.0001
MERS_PD	-0.000036	0.000004	-8.01	<.0001
MERS_stealth	-0.001423	0.000453	-3.14	0.0028
(Enemy_numAgents-12.5152)*(MERS_stealth-51.2121)	0.0003225	0.00011	2.92	0.0051
(MERS_PD-4509.09)*(MERS_stealth-51.2121)	-5.114e-7	2.353e-7	-2.17	0.0344
(Enemy_numAgents-12.5152)*(Enemy_numAgents-12.5152)	-0.003155	0.000767	-4.11	0.0001
(MERS_numAgents-15.0606)*(MERS_numAgents-15.0606)	0.0022467	0.000934	2.41	0.0197
(Enemy_PK-4509.09)*(Enemy_PK-4509.09)	-1.121e-8	2.954e-9	-3.80	0.0004
(MERS_PK-4509.09)*(MERS_PK-4509.09)	5.6675e-9	2.874e-9	1.97	0.0540
(MERS_PD-4509.09)*(MERS_PD-4509.09)	7.2386e-9	2.992e-9	2.42	0.0191

Note: all included main effects are significant at the 0.05 level.

Residual by Row Plot

The residuals display the desired pattern (or lack there of).

Interaction Profiles
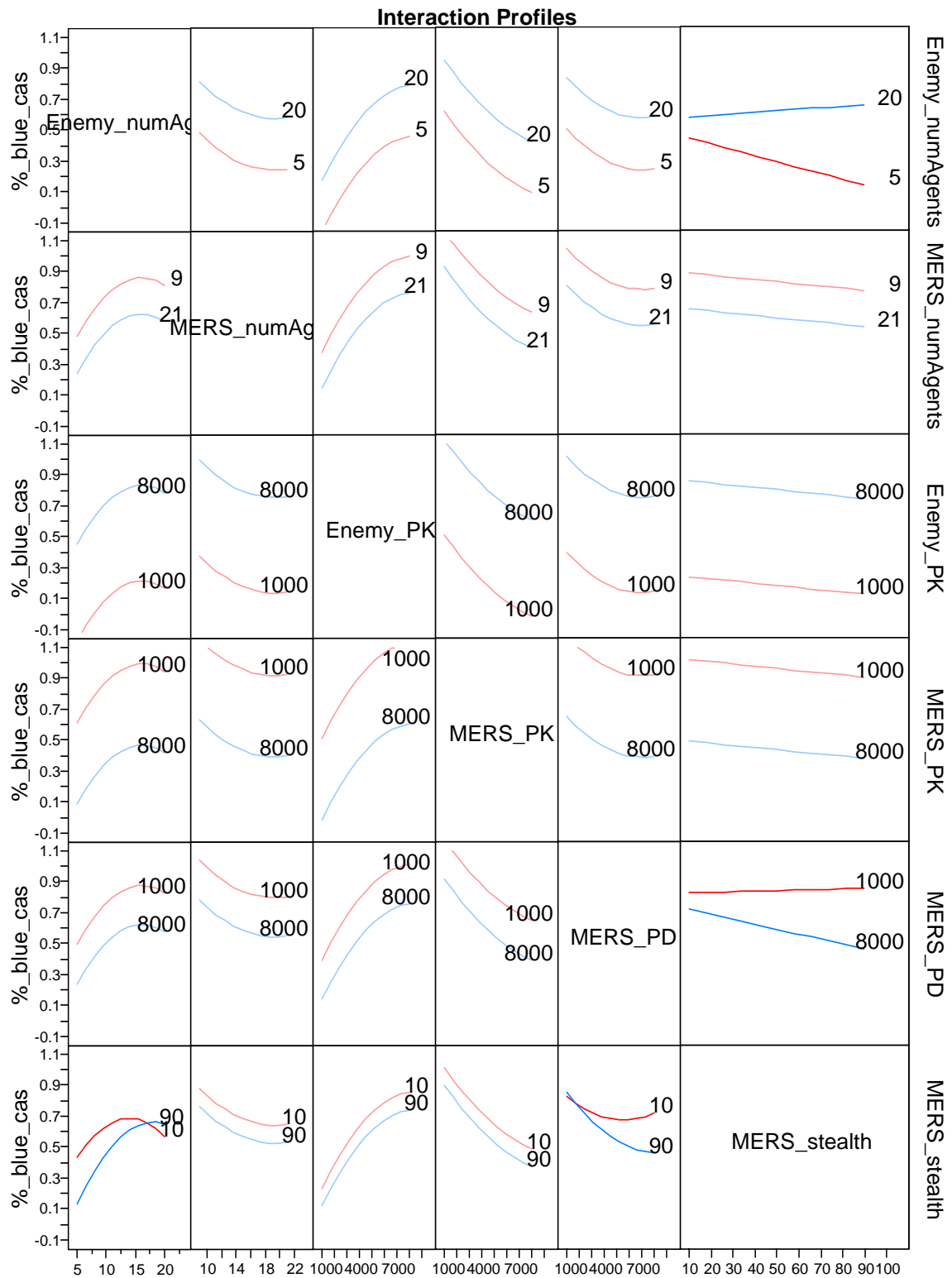
Terms with an interaction are solid lines.

B.   PREFERRED MODEL: PROPORTION OF FRIENDLY CASUALTIES

See IV. Data Analysis, B. Methodology Example: Proportion of Friendly Casualties for a more in depth explanation.

Actual by Predicted Plot
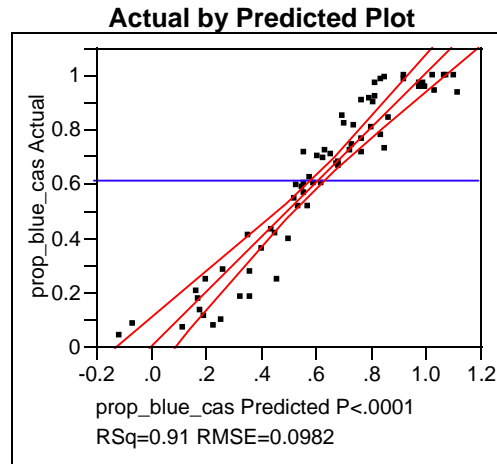
Summary of Fit

RSquare	0.905413
RSquare Adj	0.893997
Root Mean Square Error	0.098184
Mean of Response	0.614596
Observations (or Sum Wgts)	66

The amount of explained variation in the model is 0.9054 with a model variance of 0.098 (a very good fit).

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.8361842	0.078373	10.67	<.0001
Enemy_numAgents	0.0183289	0.002663	6.88	<.0001
MERS_numAgents	-0.01924	0.003357	-5.73	<.0001
Enemy_PK	0.0000877	0.000006	15.19	<.0001
MERS_PK	-0.000074	0.000006	-12.85	<.0001
MERS_PD	-0.000035	0.000006	-6.11	<.0001
(Enemy_numAgents-12.5152)*(MERS_numAgents-15.0606)	0.0014966	0.000904	1.65	0.1034
(Enemy_numAgents-12.5152)*(Enemy_numAgents-12.5152)	-0.003052	0.000658	-4.64	<.0001

Residual by Predicted Plot

The residuals display the desired pattern (or lack there of).

Interaction Profiles
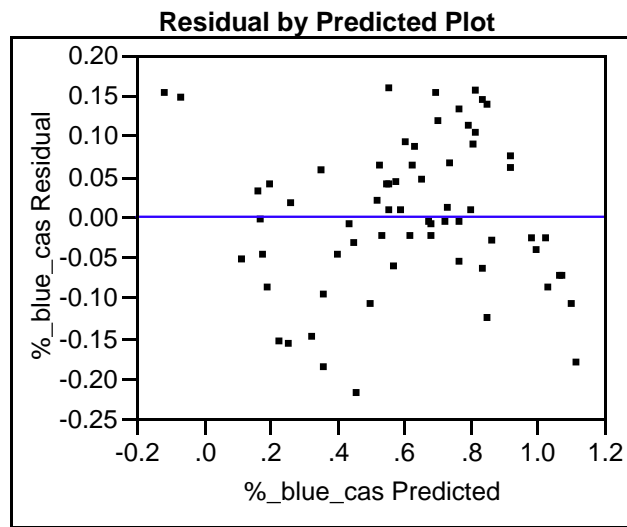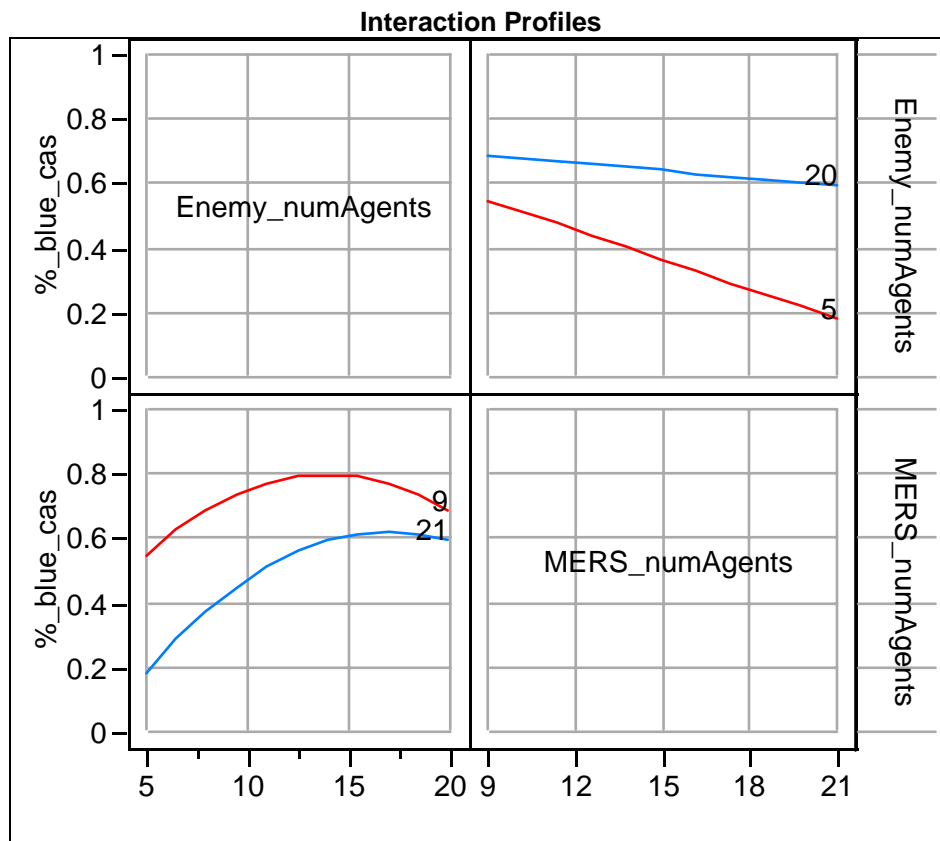
This model only contains the interactions between MERS and enemy number of agents and enemy with itself.

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APPENDIX D. MANA SCENARIO SETTINGS

The scenario settings below are in order to establish the base scenario with the initial starting conditions. It should be noted that the actual parameter values utilized varied widely (see Appendix C. Designs of Experiment). Any values that are missing or parameter not listed should be assumed to be zero.

ID	Name of Agent	State	Duration (special setting)	Fallback State	Summary
1	Insurgent	1 Default State			Start state and Default fallback state
		49 Spare 1	150 (Can't interrupt)	Taken Shot (Phi)	Left empty for use as intermediate fallback states
		5 Shot At (Phi)	10	Taken Shot (Phi)	Agent state when shot at by an enemy's primary weapon (may not have been hit)
		3 Taken Shot (Phi)	10 (interrupter)	Spare 1	Agent state when agent has fired its primary weapon at an enemy (may not have hit target)
2	Non-combatants	31 Refuel By Neutral	150	Default	Agent state while being refuelled by a neutral
		30 Refuel By Friend	150	Default	Agent state while being refuelled by a friend
		29 Refuel by Enemy	150	Default	Agent state while being refuelled by an enemy
		1 Default State			Start state and Default fallback state
3	MERS	1 Default State			Start state and Default fallback state
		3 Taken Shot (Phi)	3	Default	Agent state when agent has fired its primary weapon at an enemy (may not have hit target)
		5 Shot At (Phi)	30	Default	Agent state when shot at by an enemy's primary weapon (may not have been hit)
		13 Squad Shot At (Phi)	30 (Can't interrupt)	Default	Squad state when a squad agent has been shot at by an enemy's primary weapon (may not have been hit)

Section	Attribute	1	2	3	4	5	6	7	8	9	10	11	12
Agent SA	Enemies	20	-10			-100	-100	-100	20	40		40	40
Agent SA	Uninjured Friends			20	20								
Agent SA	Cluster	410	410	410	410								
Agent SA	Next Waypoint			40	30								
Agent SA	Easy Going									-80			
Agent SA	Cover	30	40	10	10	10	30	30		40			
Agent SA	Concealment	30	30										
Squad SA	Enemy Threat 1	50	50	50		40	40	40	40		40		
Ranges	Icon	3	3	3	2	51	51	51	51	27	27	27	51
Ranges	Allegiance	1	1	1	1	0	0	0	0	2	2	2	2
Ranges	Threat	1	1	1	1	1	1	1	1	3	3	3	1
Ranges	Movement Speed	25	50	100	100	150	150	150	10	10	100	100	10
Ranges	No Hits to kill	1	1	1	1	1	1	1	1	1	1	1	1
Ranges	Stealth	80	80						50				80
Ranges	Waypoint Radius	2	2	2	2	2	2	2	2	2	2	2	2
Ranges	Sensor Class Range	2 100 0.05	2 100 0.05	2 100 0.05	2 100 0.05	100	100	100	100	100	100	100	100
Ranges	Sensor Detect Range	1000	1000	1000	1000	100	100	100	100	100	100	100	100
Ranges	Refuel Trigger Range	50	50			30	30	30		30	30		30
Ranges	Prob Refuel Enemy												
Ranges	Prob Refuel Friend												
Ranges	Prob Refuel Neutral	100	100			100	100	100			100	100	
Weapon 1	Type	100 Kinetic energy/Agent SA	100 Kinetic energy/Agent SA	Kinetic energy/Agent SA	Kinetic energy/Agent SA				Kinetic energy/Agent SA	Kinetic energy/Agent SA	100 Kinetic energy/Agent SA	100 Kinetic energy/Agent SA	Kinetic energy/Agent SA
Weapon 1	Range	300	300	300	300				300	300	300	300	300
Weapon 1	Prob Hit	0.3	0.3	0.3	0.3				0.3	0.3	0.3	0.3	0.3
Weapon 1	Max Targets/Step	100	100	100	100				100	100	100	100	100
Weapon 1	Targets Unknowns Pause	-1	-1	-1	-1				-1	-1	-1	-1	-1
Weapon 1	Max Target Threat Level	3	3	3	3				3	3	3	3	3
Weapon 1	Max SA Target Age	100	100	100	100				100	100	100	100	100
Squad SA	Intra-Squad Comms Delay												
Squad SA	Squad Threat Persistence	150	150	150	150	50	50	50	50	50	50	50	50

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LIST OF REFERENCES

Carlson, *MERS Brief – conference I 042604v2*, power point file, Titan Corporation, 26 April 2004.

Cioppa, T. M., Efficient Nearly Orthogonal and Space-filling Experimental Designs for High-dimensional Complex Models, Ph.D. Dissertation, Naval Postgraduate School, Monterey, CA, 2002.

Cioppa, T. and L. Brown, *Agent Based Models as an Exploratory Analysis Approach to Combat Simulations*, U.S. Army TRADOC Analysis Center, Monterey, CA, 2002.

Fleet Marine Force Manual (FMFM) 6-5, *Marine Infantry Squad*.

Hagee, M. W., ALMAR 018/05, 18 April 2005.

Hagee, M. W., *Commandant's vision focuses on Marines, extends Corps' capabilities for future conflicts*, article by Fisher, Cindy SSgt., from www.usmc.mil, last accessed 13 May 2005, story ID # 20055910581, 9 May 2005.

MANA User Manual version 3.0 (draft), Galligan, Anderson, and Lauren, July 2004.

Marine Corps Future Operations Division, Draft Report: *Distributed Operations, Version 0-6*, 7 December 2004.

Marine Corps Studies and Analysis Division, Untitled Report: *(Marine Expeditionary Rifle Squad)*, 1 November 2004.

Marine Corps Warfighting Laboratory, *X-File 3-15.31 Designated Marksman; Precision Fire in the Marine Squad*, 2 June 2000.

Schmiddle, R. E. and Hoffman, F. G., *Commanding The Contested Zones*, Proceedings, September 2004.

Wikipedia, *Emergence*, www.wikipedia.org/wiki/Emergence, last accessed 03 September 2005.

West, F. J. "Bing", *The Fall of Fallujah*, Marine Corps Gazette, July 2005.

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